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Flat-Plate
Solar Array Project

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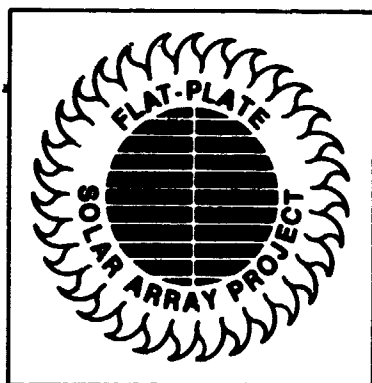
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Progress Report 20

for the Period November 1981 to April 1982

and Proceedings of the
20th Project Integration Meeting



Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 82-48)

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(JPL PUBLICATION 82-43)

Prepared by the Jet Propulsion Laboratory, California Institute of Technology,
for the U.S. Department of Energy through an agreement with the National
Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of
Energy and is part of the Photovoltaic Energy Systems Program to initiate a
major effort toward the development of cost-competitive solar arrays.

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ABSTRACT

This report describes progress made by the Flat-Plate Solar Array Project during the period November 1981 to April 1982. It includes reports on project analysis and integration; technology research in silicon material, large-area silicon sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis. It includes a report on, and copies of visual presentations made at, the 20th Project Integration Meeting held at Pasadena, California, on April 21 and 22, 1982.

NOMENCLATURE

1st Iter. 2462j

ac	Alternating current
A	Ampere(s)
Å	Angstrom(s)
ACM	Atmospheric corrosion monitors
AIAA	American Institute of Architects Foundation
AG	Allocation Guideline
AM	Air Mass (e.g., AM1 = unit air mass)
AR	Antireflective
BOS	Balance of System (non-array elements of a PV system)
CER	Controlled-environment reactor
CVD	Chemical vapor deposition
Cz	Czochralski (classical silicon crystal growth method)
dc	Direct current
DCS	Dichlorosilane
DLTS	Deep-level transient spectroscopy
DOE	U.S. Department of Energy
EBIC	Electron-beam-induced current
EDAX	Electron-dispersive analysis of X-rays
EFG	Edge-defined film-fed growth (silicon ribbon growth method)
EMA	Ethylene methylacrylate
EPDM	Ethylene-propylene-diene monomer
EPR	Ethylene propylene rubber
EPSPU	Experimental process system development unit
ESB	Electrostatic bonding
ESGU	Experimental sheet growth unit
EVA	Ethyl vinyl acetate
FAST	Fixed-abrasive slicing technique

FBR	Fluidized-bed reactor
FSA	Flat-Plate Solar Array Project
FSR	Free-space reactor
FTIR	Fourier transform infrared
GC	Gas chromatography
HEM	Heat-exchange method (silicon-crystal ingot-growth method)
HTSA	Hydrothermal stress analysis
I_{sc}	Short-circuit current
I-V	Current-voltage
ID	Inside diameter
ILA	Intermediate-load applications
ILC	Intermediate-load center
IPEG	Interim Price Estimation Guidelines
IPEG4	Improved Price Estimation Guidelines
JPL	Jet Propulsion Laboratory
kW	Kilowatt(s)
LAPSS	Large-area pulsed solar simulator
LAS	Large-Area Silicon Sheet Task
LASS	Low-angle silicon sheet growth method
LeRC	Lewis Research Center
m	Meter(s)
MBS	Multiblade sawing
MEPSDU	Module experimental process system development unit
mgSi	Metallurgical-grade silicon
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MLAR	Multilayer antireflective coating
mm	Millimeter(s)
MT	Metric ton(s)

NASA	National Aeronautics and Space Administration
NBNM	Natural Bridges National Monument
NDE	Non-destructive evaluation
NMR	Nuclear magnetic resonance
NOC	Nominal operating conditions
NOCT	Nominal operating cell temperature
NTE	Nominal thermal environment
O&M	Operation and maintenance
OD	Outside diameter
P	Individual module output power
P_{avg}	Average module output power
P_{avg}	Module rated power at SOC, V_{no}
P_{max}	Maximum power
P_{min}	Minimum acceptable output power
P/FR	Problem-failure report
PDU	Process development unit
PEBA	Pulsed electron beam annealing
PIM	Project Integration Meeting
PMMA	Polymethyl methacrylate
PnBA	Poly-n-butyl acrylate
PO	Purchase order
PRDA	Program Research and Development Announcement
PV	Photovoltaic(s)
PV/T	Photovoltaic-thermal
PVB	Polyvinyl butyral
QA	Quality assurance
QUV	Ultraviolet chamber (trade name)
R&D	Research and development

RES	Residential Experiment Station
RFP	Request for proposal
RTR	Ribbon-to-ribbon (silicon crystal growth method)
RTV	Room-temperature vulcanized
SAIPEG	Sensitivity analysis using IPEG
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SCIM	Silicon coating by inverted meniscus
SEM	Scanning electron microscope
SEMI	Semiconductor Equipment Manufacturers Institute
SERI	Solar Energy Research Institute
SIMS	Secondary ion mass spectroscopy
SOC	Standard operating conditions (module performance)
SOC	Silicon on ceramic (crystal growth method)
SOLMET	Solar radiation surface meteorological observations
SPV	Surface photovoltage
STC	Silicon tetrachloride
TCS	Trichlorosilane
TEM	Transmission electron microscope
TR	Technical Readiness
UCP	Ubiquitous crystallization process
UV	Ultraviolet
V	Volts(s)
V _{dc}	Direct-current voltage
V _{no}	Nominal operating voltage
V _{oc}	Open-circuit voltage
W	Watt(s)
W _p	Peak watt(s)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures				Approximate Conversions from Metric Measures			
Symbol	When You Know	Multiply by	To Find	Symbol	When You Know	Multiply by	To Find
LENGTH				LENGTH			
in	inches	2.5	centimeters	mm	millimeters	0.04	inches
ft	feet	30	centimeters	cm	centimeters	0.4	inches
yd	yards	0.9	meters	m	meters	3.3	feet
mi	miles	1.6	kilometers	km	kilometers	1.1	yards
						0.6	miles
AREA				AREA			
sq in	square inches	6.5	square centimeters	sq cm	square centimeters	0.16	square inches
sq ft	square feet	0.09	square meters	sq m	square meters	1.2	square yards
sq yd	square yards	0.8	square meters	sq km	square kilometers	0.4	square miles
sq mi	square miles	2.6	square kilometers	ha	hectares (10,000 m ²)	2.6	acres
	acres	0.4	hectares				
MASS (weight)				MASS (weight)			
oz	ounces	28	grams	g	grams	0.035	ounces
lb	pounds	0.45	kilograms	kg	kilograms	2.2	pounds
	short tons (2000 lb)	0.9	tonnes	t	tonnes (1000 kg)	1.1	short tons
VOLUME				VOLUME			
cup	teaspoons	5	milliliters	ml	milliliters	0.035	fluid ounces
fl oz	tablespoons	15	milliliters	l	liters	2.1	pints
c	fluid ounces	30	milliliters	m ³	cubic meters	1.06	quarts
pt	gallons	0.24	liters			0.26	gallons
qt	pints	0.47	liters			26	cubic feet
gal	quarts	0.96	liters			1.3	cubic yards
cu ft	gallons	3.8	cubic meters				
cu yd	cubic feet	0.03	cubic meters				
	cubic yards	0.76	cubic meters				
TEMPERATURE (exact)				TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature

* 1 in x 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Mon. Publ. 286, Units of Weights and Measures, Price \$2.25, SO Catalog No. C13.10.286.



CONTENTS

PROGRESS REPORT

PROJECT SUMMARY	1
AREA REPORTS	3
ANALYSIS AND INTEGRATION AREA	3
PHOTOVOLTAIC COMPONENTS RESEARCH AREA	5
Advanced Materials Research Task	5
Device and Measurements Research Task	19
Environmental Isolation Task	22
CELL AND MODULE FORMATION RESEARCH AREA	31
ENGINEERING SCIENCES AREA	35
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA	43

Tables

1. Advanced Materials Research Task Contractors	7
2. Device and Measurements Research Task Contracts	20
3. Test Results for Block IV Modules	47

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PROCEEDINGS

INTRODUCTION	51
PLENARY SESSION	55
NATIONAL PHOTOVOLTAICS PROGRAM (M. Prince, U.S. Department of Energy)	55
FSA's FUTURE ROLE (W.T. Callaghan, JPL)	61
UNION CARBIDE CORP. POLYSILICON STATUS AND PLANS (M.H. Leipold, JPL)	67
ADVANCED CZOCHRALSKI INGOT GROWTH (R.L. Lane, Kayex Corp.)	71
BLOCK V MODULE DESIGN SUMMARY (L.D. Runkle, JPL)	99
CENTRAL-STATION APPLICATIONS: SYSTEM AND SUBSYSTEM RESEARCH ACTIVITIES (G.J. Jones, Sandia National Laboratories)	105
PV LARGE SYSTEMS PROJECT (S.L. Leonard, Aerospace Corp.)	113
SACRAMENTO MUNICIPAL UTILITY DISTRICT 100-MW _e PHOTOVOLTAIC POWER PLANT (R.V. Powell, JPL)	123
ENERGY ECONOMICS: DOES PHOTOVOLTAICS FIT IN? (M. Sagenkahn, Shell Oil Co.)	125
PV HISTORY: LESSONS FOR THE FUTURE (E.L. Ralph, Spectrolab, Inc.)	131
UTILITIES PERSPECTIVE (R.W. Taylor, Electric Power Research Insititute)	135
ROOFTOP APPLICATIONS (E. Kern, Massachusetts Institute of Technology Lincoln Laboratory)	147
PV RESEARCH NEEDS: INDUSTRY PERSPECTIVE (R. Little, Spire Corp.)	151
PV RESEARCH NEEDS: INDUSTRY PERSPECTIVE (K. V. Ravi)	155
RESEARCH POSSIBILITIES? NO! NEEDS FOR RESEARCH TO MAKE PV SOLAR ENERGY UTILIZATION BROADLY COMPETITIVE (M. Wolf, University of Pennsylvania)	161
EVALUATION OF ADVANCED R&D TOPICS IN PHOTOVOLTAICS (T. Surek, Solar Energy Research Institute)	171

TECHNOLOGY SESSIONS	179
FLAT-PLATE COLLECTOR RESEARCH AREA	
SILICON MATERIAL TASK	179
Silane-to-Silicon Process (Union Carbide Corp.)	180
Hydrochlorination Process (Solarelectronics, Inc.)	186
Dichlorosilane CVD Process (Hemlock Semiconductor Corp.)	196
In-House Material Research Program: Si Deposition in FBR System (JPL)	215
LARGE-AREA SILICON SHEET TASK	227
Advanced Dendritic Web Growth Development (Westinghouse Electric Corp.)	230
Edge-Defined Film-Fed Growth (Mobil Tyco Solar Energy Corp.)	238
Semicrystalline Process Development (Semix Inc.)	246
Advanced Czochralski Ingot Growth (Kayex Corp.)	267
Material Characterization (Cornell University)	274
Grain Boundary Investigation (JPL)	289
Study of Abrasive-Wear Rate of Silicon (University of Illinois at Chicago)	305
Solar Cell Fabrication and Analysis (Applied Solar Energy Corp.)	314
ENVIRONMENTAL ISOLATION TASK	321
Encapsulation Technology Available (JPL)	322
Material Research and Evaluation (Springborn Laboratories, Inc.)	326
Encapsulant Design Analysis and Verification (Spectrolab, Inc.)	352
Photoacoustic Technique (JPL)	356
Minimodule Encapsulant Field Testing (JPL)	358
CELL AND MODULE FORMATION RESEARCH AREA	363
Thick-Film Metallization (Bernd Ross Associates)	365

Optimization Program/Design Method for Solar Cell Grid Patterns (JPL)	378
Thick-Film Metallization (Spectrolab, Inc.)	384
Nickel/Copper Metallization (Photowatt International, Inc.)	386
Ion Implantation and Pulse Annealing (Spire Corp.)	390
Non-Mass-Analyzed Ion Implantation (JPL)	401
Process Research: Semix Silicon Material (Solarex Corp.)	404
MEPSDU (Westinghouse Electric Corp.)	410
Dendritic Web Silicon (Westinghouse Electric Corp.)	414
Photovoltaic Assessment (University of Pennsylvania)	418
 ENGINEERING SCIENCES AREA AND MODULE PERFORMANCE AND FAILURE ANALYSIS AREA	
PV Array/Power Conditioner Interface Update (JPL)	429
Array Degradation and Voltage Control Strategies (Massachusetts Institute of Technology Lincoln Laboratory)	440
I-V Curve Data Base and Applications (Massachusetts Institute of Technology Lincoln Laboratory)	460
Irradiance Data for JPL Test Site (JPL)	467
AM1.5 Filtering System for LAPSS (JPL)	471
Residential Array Research (JPL)	479
Voltage Breakdown of PV Insulating Materials (JPL)	487
Leakage Current in Encapsulants (JPL)	500
Cell Reliability Testing (JPL)	509
Long-Term Module Testing (JPL)	512
Preliminary Long-Term Testing Results (JPL).	520
 ANALYSIS AND INTEGRATION AREA	
Machine/Operator Requirement Simulations (JPL)	530

PROGRESS REPORT

Project Summary

INTRODUCTION

This report describes the activities of the Flat-Plate Solar Array (FSA) Project from November 1981 to April 1982, including the 20th FSA Project Integration Meeting (PIM), held on April 21 and 22, 1982.

The FSA Project, sponsored by the U.S. Department of Energy (DOE), has the responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources. This responsibility has included developing the technology for producing low-cost, long-life photovoltaic modules and arrays. More than 100 organizations have participated in FSA-sponsored research and development of low-cost solar module manufacturing and mass production technology, the transfer of this technology to industry for commercialization, and the development and testing of advanced prototype modules and arrays. Economic analyses were used to select, for sponsorship, those research and development efforts most likely to result in significant cost reductions. Set forth here is an account of the progress that has been made during the reporting period.

SUMMARY OF PROGRESS

Start-up tests are planned for July 1982 on the silane portion of the Union Carbide Corp. (UCC) experimental process system development unit (EPSDU) in Washougal, Washington, where construction continues under UCC funding. The silane EPSDU equipment title was transferred to UCC in exchange for EPSDU operational data. The research study of silane-to-silicon deposition in an experimental 2-in.-dia fluidized-bed reactor has been successfully completed.

Hemlock Semiconductor Corp. continues to operate its process development unit (PDU) integrated with a silicon (Si) deposition reactor from which Si of excellent purity is produced.

Mobil Tyco Solar Energy Corp. made 11.7%-efficient (AM1 and antireflective-coated) cells on edge-defined film-fed growth (EFG) ribbons grown at high speed (3.5 cm/min).

Kayex Corp. completed its efforts on advanced Czochralski silicon-ingot growth which included automated growth of five 15-cm-dia ingots totaling 150 kg from one crucible. The crucible was replenished with chunk silicon after each ingot pull without cooling down the furnace.

Progress continues on experimentation with ethylene methyl acrylate as a possible encapsulation pottant; on faster, lower temperature curing agents for ethylene vinyl acetate; on a primer for bonding poly-n-butyl acrylate to glass; on UV absorbers for pottants, and on encapsulant material durability and life testing.

PROGRESS REPORT

Five months of outdoor soiling on untreated glass (Sunadex) resulted in a 3% loss of current (I_{sc}); a Sunadex glass treated with a fluorinated material caused a loss of only 0.5% in I_{sc} .

Westinghouse Electric Corp. has completed its rolling-spot ultrasonic bonding technique activities with the completion of its fabrication machine.

University of Pennsylvania has completed its assessment of metallization design optimization methods. JPL has also performed metallization pattern studies.

Proposed photovoltaic module design safety requirements were accepted in principle by the voting members of the National Electrical Code (NEC) Panel 3. It is expected that the proposed 1984 code will be released for public comment in June 1982.

Progress continues in research on electrical and fire-safety requirements; protective bypass diodes for modules; determining appropriate power-conditioning voltage, current, and power levels versus array parameters; integrated residential arrays, and module engineering activities including cell-reliability testing, module voltage isolation, interconnect fatigue, cell-fracture mechanics, and reliability/durability studies.

Six contractors completed Block V module preliminary designs. No contracts were awarded for prototype module fabrication because of a lack of funds.

Six sets of modules were tested to Block V specifications for the Georgetown Project. The results have been provided to Georgetown University and Oak Ridge operations personnel.

Area Reports

PROJECT ANALYSIS AND INTEGRATION AREA

INTRODUCTION

The objective of the Project Analysis and Integration Area is to support the planning, analysis, integration, and decision-making activities of the Project. This is done by developing and documenting Project plans, and by contributing to the generation and development of alternative Project plans through the assessment of technology options; by establishing standards for economic comparison of options under Project study and developing the analytical capabilities to perform the trade-offs required; by supporting the integration of the tasks within the Project and between the Project and other elements of the National Photovoltaics Program, and by providing coordinated assessments of progress toward the achievement of Project goals by the various areas of the Project working with the solar-array manufacturing industry and the National Photovoltaics Program.

SUMMARY OF PROGRESS

In November 1981 a two-day short course on the effective use of SAMICS was presented. Thirteen companies including several outside the National Photovoltaics Program sent representatives to the course, representing a mix of program managers, engineers, and financial analysts. The theory underlying the SAMICS approach to computing required revenue prices was presented. The course, however, emphasized practical applications of the use of SAMICS by means of detailed explanations and demonstrations. A summary of course material has been documented: Solar Array Manufacturing Industry Costing Standards (SAMICS), Short Course, JPL Document No. 5101-196.

SAMIS Release 4 preparation and documentation was a major undertaking since the last PIM. Significant changes in SAMIS have been incorporated in the new release:

- (1) The SAMIS cost catalog has been revised and updated, including the section on effluent requirement costs, which are now derived by specifying effluent quantities as byproducts on Format A's.
- (2) The financial reports have been improved by revisions in the one-time costs model and the inclusion of year-by-year financial reports.
- (3) The input formats have been redesigned and the User's Manual, Design Document, and the Computer Source Codes have all been updated.
- (4) A companion document, Summary Guide to Using SAMIS, is being distributed as part of SAMIS Release 4 along with an abridged version of the Cost Account Catalog. The former should enable the first-time user to operate the program more readily.

PROJECT ANALYSIS AND INTEGRATION AREA

The SAMIS Release 4 documents and reference numbers are:

SAMIS User's Reference Card, JPL Document No. 5101-183.
SAMIS User's Guide, JPL Document No. 5101-60.
SAMIS Design Document, Revision C, JPL Document No. 5101-70.
SAMIS Computer Program Source Code, Revision C, JPL Document No. 5101-71.
SAMIS Cost Account Catalog (revisions are on line).
Summary Guide to Using SAMICS, JPL Document No. 5101-193.
Abridged Cost Account Catalog, JPL Document No. 5101-191.

An introduction to the SIMRAND (SIMulation of Research AND Development) computer program has been published (JPL Document No. 5101-204). SIMRAND was designed as a management tool for ranking alternative R&D project tasks. The methodology uses analytical techniques of probability theory, decision analysis, and computer simulation to select an optimal set of R&D tasks.

Analysis of optimal manpower requirements and downtime of industrial PV manufacturing equipment was initiated at the beginning of the quarter. A methodology was designed to estimate requirements based on the adaptation of a queueing model to a probabilistic production costing model for electric power systems. A computer program that incorporates the new methodology has been implemented on a microcomputer system.

An economic assessment of the Westinghouse MEPSDU is nearing completion. Differences between Westinghouse and FSA data inputs have been reconciled and new Format A's have been processed for a SAMICS analysis of a 25-megawatt denbritic-web factory.

An analysis of PV energy payback times was presented at the DOE Annual Review in Washington. The analysis showed energy payback times for modules using technology that will be available by mid-decade to be 0.6 to 1.1 years, and system energy payback to be two to five years depending on system efficiency. Reports published in various popular and technical journals have asserted that PV energy payback times are in the 10- to 20-year range. These neglected to include the advances in technology resulting from the DOE PV program and assumed a new-technology status similar to that in 1974.

A new Allocation Guideline (AG) is being developed for FSA. This new AG reflects revised priorities of the Photovoltaics Program and includes guidelines for PV array subsystems.

The development and validation of the metallization grid design program is continuing. Laboratory verification of the predictions of the grid design program will be attempted in the coming months.

PHOTOVOLTAIC COMPONENTS RESEARCH AREA

During this reporting period FSA restructured a portion of its organization in order to concentrate its efforts toward research on the key high-risk technologies necessary for advancement of the photovoltaics industry in the late 1980s and into the 1990s. As a result of this action the Silicon Material and Large-Area Silicon Sheet Tasks have been reorganized into two new Tasks, Advanced Materials Research and Device and Measurements Research.

Advanced Materials Research Task

INTRODUCTION

The objective of the Advanced Materials Research Task is to identify the critical technical barriers to low-cost silicon (Si) purification and sheet growth that must be overcome to produce a photovoltaic cell substrate material at a price consistent with FSA objectives and then to perform and support research and development to address those barriers.

Present solar-cell technology is based on the use of silicon wafers obtained by ID slicing of Czochralski (Cz)-grown ingots from Siemens-reactor-produced semiconductor-grade silicon. This method of obtaining single-crystal silicon wafers is tailored to the needs of large-volume semiconductor device production (e.g., integrated circuits and discrete power and control devices other than solar cells). The small market offered by present solar-cell users does not justify industry's development of the high-volume silicon production techniques that would result in low-cost photovoltaic electrical energy.

It is important to develop and demonstrate the feasibility of several processes for producing refined silicon and sheet material suitable for long-life, high-efficiency solar photovoltaic energy conversion. To meet the objective of FSA, sufficient research must be performed on a number of techniques to determine the capability of each of producing large areas of crystallized silicon at a low, competitive cost. The sheet-growth configurations must be suitable for direct incorporation into an automated solar-array industry scheme.

FSA-funded improvements of the standard Czochralski ingot-growth process by reduction of expendable material costs and improvement of ingot growth rate together with improved slicing techniques have developed the technology so that large areas of silicon can be produced at costs approaching the 1982 FSA goals. Growth of large ingots by casting techniques, such as the ubiquitous crystallization process (UCP), may reduce sheet costs further.

Research and development of multiblade, multiwire, and inside-diameter blade ingot cutting, initiated in 1975-76, was terminated recently in accordance with DOE guidelines.

ADVANCED MATERIALS RESEARCH TASK

Growth of crystalline silicon material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG) and dendritic-web growth (web) are candidates for such solar-cell material.

Advanced Materials Research Contracts

Ongoing research and development contracts awarded for semiconductor-grade silicon processes and for growing crystalline silicon material for solar cell production are listed in Table 1.

SUMMARY OF PROGRESS

Semiconductor-Grade Silicon Processes

Battelle Columbus Laboratories

Three contracts in this category were active. Battelle Columbus Laboratories issued its final report on investigating the production of Si by the zinc reduction of silicon tetrachloride (STC). The contract was given a no-cost extension to the end of December 1981 to allow Battelle to conduct a conceptual analysis of an improved design developed from a critique of the process development unit (PDU) that was used to investigate the process.

Battelle's conceptual analysis is of four major units of the zinc/silicon tetrachloride process (fluidized-bed reactor, byproduct condenser, electrolytic cell, and zinc vaporizer) and was submitted on January 14, 1982. Operating failures and design deficiencies of the PDU were outlined. Modification of reactor designs was suggested; e.g., an inductively heated cold-wall reactor was proposed. Battelle emphasized that the overall process concept was still an attractive alternative for meeting the low-cost goal in silicon production.

Hemlock Semiconductor Corp.

Hemlock Semiconductor Corp. is investigating a process for making semiconductor-grade silicon (Si) in which dichlorosilane (DCS) is made from trichlorosilane (TCS) by a redistribution reaction using an organic amino functional catalyst, and the DCS is then reduced by hydrogen to produce Si in a chemical-vapor deposition step using a Siemens-type reactor.

Hemlock continued to operate the DCS process development unit (PDU), integrated with Si deposition reactors, to investigate conversion of TCS to DCS and decomposition of the latter to Si. The 5-in.-dia redistribution reactor was used in the PDU. At the end of December this reactor had produced 54,950 lb of DCS. Catalyst performance has been excellent, with no observable degradation in performance.

Late in December the PDU was shut down for the holidays. During restart in January, extremely cold weather froze some of the equipment. In the course of shutting down the unit, a screen that retains catalyst in the redistribution

ADVANCED MATERIALS RESEARCH TASK

Table 1. Advanced Materials Research Task Contractors

Contractor	Technology Area
<u>Semiconductor-Grade Silicon Processes</u>	
Battelle Columbus Laboratories Columbus, Ohio JPL Contract No. 954339	Reduction of SiCl_4 by Zn in fluidized-bed reactor
Hemlock Semiconductor Corp. Hemlock, Michigan JPL Contract No. 955533	Dichlorosilane CVD process
Union Carbide Corp. Tonawanda, New York JPL Contract No. 954334	Silane-Si process
<u>Ingot Technology</u>	
Crystal Systems, Inc. Salem, Massachusetts JPL Contract No. 954373	Heat exchanger method (HEM) ingot growth; fixed-abrasive slicing technique (FAST)
Kayex Corp. Rochester, New York JPL Contract No. 955733	Advanced Cz growth (Adv. Cz)
Semix Inc. Gaithersburg, Maryland DOE Contract No. DE-F101-80ET 23197	Ubiquitous crystallization process (UCP)
Silicon Technology Corp. Oakland, New Jersey JPL Contract No. 955131	Internal diameter (ID) slicing
P.R. Hoffman Co. Carlisle, Pennsylvania JPL Contract No. 955563	Multiblade slurry slicing technique (MBS)
<u>Shaped Sheet Technology</u>	
Mobil Tyco Solar Energy Corp. Waltham, Massachusetts JPL Contract No. 954355	Edge-defined film-fed growth (EFG)
Westinghouse Electric Corp. Pittsburgh, Pennsylvania JPL Contract No. 955843	Dendritic web growth (web)

ADVANCED MATERIALS RESEARCH TASK

Table 1. Advanced Materials Research Task Contractors (Cont'd)

<u>Supporting Studies</u>	
Solarelectronics, Inc. Bellingham, Massachusetts JPL Contract No. 956061	Hydrochlorination of metallurgical-grade Si and SiCl ₄
Texas Research and Engineering Institute Groves, Texas JPL Contract No. 956045	Technology and economic analyses
University of Illinois Chicago, Illinois JPL Contract No. 956053	Study of abrasive rate of Si

reactor broke loose, allowing catalyst to enter other portions of the system including the DCS distillation column. The catalyst was flushed out, the distillation column was repacked, and modifications were made to the PDU to prevent recurrence of the accident. The PDU was put back into operation in March and has been operating well.

The Model IID Si deposition reactor was successfully integrated with the PDU, constituting the first operation of this large-sized, advanced reactor on DCS. The PDU has been feeding a large-sized and an intermediate-sized reactor simultaneously. In the longest test, of about 90-hour duration, a Si deposition rate of 1.67 g/h·cm and a 33.9% conversion of DCS to Si were achieved in the large reactor. Both of these values are lower than the program goals (2 g/h·cm and 40%, respectively), but the testing of the large reactor is still in its early stages. The purity of the Si being produced (semiconductor-grade) is excellent.

Si deposition on the inside surfaces of reactor bell jars has been undesirably high in tests with DCS in intermediate-sized reactors. A system by which gaseous HCl is introduced into the deposition reactors at the ends of runs, to etch the Si from the walls preferentially, was tested and found to operate as desired. Very little Si is etched from the deposition rods, and polymer deposits on the reactor base plate are stripped, facilitating clean-up.

Union Carbide Corp.

The Union Carbide Corp. (UCC) contract has the objective of developing a process capable of the high-volume production of semiconductor-grade silicon suitable for terrestrial solar cell manufacture at a price of less than \$14/kg (1980 \$). The silane-to-silicon process being developed by UCC starts with metallurgical-grade silicon feedstock, hydrochlorination of silicon feedstock with process-recycled hydrogen and silicon tetrachloride, distillation, and redistribution over A-21 resin beds to form pure silane, followed by silane pyrolysis in a continuous fast-deposition reactor such as a fluidized-bed reactor. The silane synthesis portion is under active investigation in UCC's own pilot plant at Washougal, Washington. UCC, under JPL-DOE sponsorship, is

ADVANCED MATERIALS RESEARCH TASK

pursuing R&D studies of the essential silane pyrolysis silicon deposition step, which is immature for industrial development at this stage and is important to the development of low-cost polysilicon technology.

Silane EPSDU work continues under UCC funding at Washougal. Civil contract and building structure, except the silane decomposer, were completed. Mechanical and electrical contracts including process piping connections are under way. Start-up tests are planned for July 1982. Congress and DOE authorized JPL to transfer EPSDU equipment title to UCC in exchange for silane operation data.

Kayex Corp., a subcontractor, submitted a final report (three volumes) on the free-space reactor powder melting/consolidation R&D study. UCC transmitted to JPL 3.2 kg samples of silicon shot made from free-space reactor powders.

The fluidized-bed PDU was modified and reactivated with a new heating system. Heating experiments in hydrogen atmosphere showed that bed temperatures in the 650 to 700°C range could be achieved while maintaining a low distributor temperature of about 300°C. The temperature profiles in hydrogen tests are favorable for achieving heterogeneous deposition on particle surface while minimizing wall deposits. Silane decomposition experiments to identify the operating window are in progress. With up to 19% inlet silane, which has a higher heat capacity than hydrogen, minor engineering modifications are directed to maintain a desirable temperature distribution. Feasibilities of product withdrawal and seed introduction during the operation have been successfully checked out.

Ingot Technology

Crystal Systems, Inc. (HEM)

The Schmid-Viechnicki technique (heat-exchanger method or HEM) was developed to grow large single-crystal sapphire. Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium (the cooling medium) through the heat exchanger. This obviates motion of the crystal, crucible, or heat zone. In essence, this method involves directional solidification from the melt where the temperature gradient in the solid is controlled by the heat exchanger and the gradient in the liquid is controlled by the furnace temperature. The overall goal of this program is to determine whether the heat-exchanger ingot-casting method can be applied to the growth of large silicon crystals of 30-mm-cube dimensions of a quality suitable for the fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire-growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

The draft final report for the HEM portion of the contract was sent to JPL where it was reviewed and returned with comments. The contractor is incorporating the suggestions.

ADVANCED MATERIALS RESEARCH TASK

Kayex Corp. (Advanced Cz)

In the Advanced Cz contracts, efforts were directed toward developing equipment and a process to achieve economic objectives and to demonstrate the feasibility of continuous-Cz solar-grade crystal production. Kayex has already demonstrated the growth of 150 kg of single-crystal material, using only one crucible, by periodic melt replenishment.

The Advanced Cz contract, initiated October 1980, was completed April 30. It was the last of the FSA ingot-growth subcontracts; it will not be renewed.

Experimental activity during this reporting period included a study of cell-efficiency distribution from the ingots of a 150-kg ESGU demonstration run; the continued development of microprocessor automation, especially sensor development for the modified CG2000 ESGU grower; data collection from the real-time ambient gas analysis system installed on the grower, and initial crucible devitrification observations.

Solar cells were fabricated from wafers sliced from the tops, middles and bottoms of the ingots that composed the 150-kg ESGU demonstration growth-run product. Cell efficiencies observed were higher than those achieved in past multiple-ingot runs. Conversion efficiencies from the tops of the ingots averaged 15.3%, and from the bottoms, 12.3%, with uniform efficiencies at each level. Control samples averaged 15.8%. These results are promising.

The ESGU was retrofitted with the Hamco microprocessor-based Automatic Grower Logic (AGILE) system. Interfacing required the development of improved sensors to monitor melt seeding, diameter and shoulder control, and meltback. The AGILE system has been successfully demonstrated on three single-ingot growth runs. The melt-level sensor is not yet integrated into the closed-loop system on the modified CG2000.

This real-time ambient-gas analysis system, designed and built by Hamco to monitor the effects of process variations on ambient-gas composition, was operated on the ESGU. A close correlation of system temperature with CO and H₂ concentrations in the furnace was noted. High levels of CO at initial melt-in (5000 ppm) and spikes in CO (up to 35,000 ppm) and H₂ concentrations at crown meltback and recharge melt-in were seen.

Crucible breakdown has been suggested as a possible source of the impurities or particles that lead to ingot quality degradation. A study of the devitrification rosettes observed on the quartz crucibles after high-temperature use was begun. Hamco observed that (1) they have a structure different from the rest of the crucible, (2) the rosette nucleus contains a ring of small bubbles, (3) the rosettes grew both radially and into the crucible walls, and (4) the interior of the rosettes is clean (no impurities), but the edges contain high concentrations of metals (up to 8 1/2% oxide).

This program has been successful. The achievements are a significant improvement over conventional Cz technology. They include:

- 150 kg from one crucible (5 x 30 kg ingots)
- 15-cm-dia x 37.5 kg growth demonstrated

ADVANCED MATERIALS RESEARCH TASK

- Microprocessor controls with improved sensors
- Prototype equipment transferable to industry
- After-growth yields: 90% of melt pulled
- 15.3% AMI in monocrystal.

Goals not achieved were throughput (2.5 kg/h goal, 1.5 kg/h achieved), yield of monocrystal (90% goal, 50% achieved) and recharge melting rate (25 kg/h goal, 14 kg/h achieved). Additional developmental work on known problems could produce valuable improvements.

Semix, Inc. (Semicrystalline Casting)

The semicrystalline casting process is a Semix proprietary process yielding a polycrystalline silicon brick capable of being processed into square cells with efficiencies typically 90% of those of single-crystal cells.

A revised program was established and is being implemented. It focuses on the critical elements of four components of the Semix technology: (1) high-throughput casting, (2) wafering technologies, (3) ingot/wafer quality determinations, and (4) efficiency demonstrations. Progress in each of these will be presented in turn.

Efforts in development of high-throughput casting technology have been curtailed because of unavailability of funds to support the program; efforts involving equipment development have suffered the most. Thermal analyses of the casting process and related microstructure and efficiency studies suggest that there is an extensive crystalline order to the Semix material in which many grain boundaries are special high-order twin configurations exhibiting minimal impact on performance; this work is continuing.

Wafering efforts have investigated conventional multiblade slicing, high-speed multiblade slicing, ID, and a new advanced wafering machine. Efforts on the multiblade wafering, both conventional and high-speed, have been dropped during this report period. Conventional multiblade slicing has been dropped because the analysis indicates that it cannot be made economically competitive with ID. A report summarizing results is in preparation. High-speed multiblade slicing efforts have been discontinued because the machine available would not perform reliably. A 27-in. Silicon Technology Corp. ID wafering machine has successfully been put into operation and is now slicing 10 x 15 cm wafers, 300 μm thick, at speeds of 2 1/2 to 3 in./min. Thinner blades will be required along with some reduction in thickness to be fully competitive using semiconductor-grade silicon. Finally, a new advanced wafering machine (details proprietary) has been put into initial operation. No results are available as yet to determine its potential for success.

Efforts in material quality characterization have resulted in descriptions of a microwave excitation technique that can give information about resistivity and lifetime in a wafer by analysis of a decay of a pulse. Results indicate that the technique is a useful quality measurement tool. Related approaches for ingots are under investigation.

Slow but steady improvements in wafer quality continue. The most recent lot of 10 x 10-cm cells using new high-efficiency processing technology,

ADVANCED MATERIALS RESEARCH TASK

including thinning and back-surface fields, has resulted in an AMI efficiency range of 11.8% to 12.9%. Earlier analyses indicate that \$.70/W could be achieved at 13% average panel efficiency using fully developed casting and wafering technologies.

The fourth quarterly report has been released and the fifth has been approved for release. A summary report on conventional multiblade slicing and a proof-of-concept report have also been approved for public distribution.

Wafering Technology

Today most silicon is sliced into wafers with an inside-diameter saw, one wafer at a time. Advanced efforts in this area are continuing. Multiblade slicing uses reciprocating blade-head motion with a workpiece fed from below. Cutting is done by 5-mil steel wires surrounded by a 1.5-mil copper sheath that is impregnated with diamond as an abrasive.

The multiblade slurry technique is similar to the multiwire slicing technique, except that low-carbon steel blades (typically 1 cm in height and 6 to 8 mils thick) are used in conjunction with an abrasive slurry mixture of SiC and oil.

Silicon Technology Corp. (ID Wafering)

The slicing contract with Silicon Technology Corp. was terminated in February 1982.

Despite the foreshortened program, substantial progress was made. Much time was spent eliminating vibration problems, which were reduced by more than a factor of 2. Other changes including replacement of bearings, redirection of the coolant/lubricant jet stream and increasing fluid pressure; all contributed to the improved slicing performance.

The wafering goals of the contract included slicing 6-in.-dia ingots at 2.5 in./min with a kerf-plus-wafer thickness of 22 mils (18 wafers/cm) and yield greater than 95%. The actual results for the 6-in. ingots are: cutting rate of 3.0 in./min, kerf-plus-wafer thickness of 23 mils (17 wafers/cm) and yield of >95%. For the 10 x 10-cm ingots the goals were to slice at 1 wafer/min with a kerf-plus-wafer thickness of 16 mils (25 wafers/cm) and yield greater than 95%. At the end of the program, two 10 x 10-cm cross-section ingots were sliced at 2.5 in./min and a kerf-plus-wafer thickness of 23.5 mils (<17 wafers/cm) and yield >95%. STC has demonstrated the ability to slice 25 wafers/cm of 10-cm-dia ingots, but the slicing rates were lower.

Other areas of investigation included a blade development program that involved using thinner blades and changing the diamond profile of the blade, varying the ID/OD ratio and changing the plating parameters. Some work was also done in modifying the fluid mixture to improve the slicing performance. As expected, no results were conclusive.

ADVANCED MATERIALS RESEARCH TASK

P. R. Hoffman Co. (MBS)

Contractor activity was terminated early in the reporting period. No final report was prepared.

Crystal Systems, Inc. (FAST)

The multiwire wafering contract with Crystal Systems, Inc., was terminated in January 1982.

The slicing effort at CSI began in November 1975. During that time a prototype saw was built and an extensive wire development program was supported. The goals of the program were to slice 10 x 10-cm ingots at 0.1 mm/min, 25 wafers/cm, 5 slices/wire and a 95% yield averaged over the five slicing runs. None of the goals came close to being achieved simultaneously. The best individual achievements of the program for 10-cm-dia ingots: 25 wafers/cm, 0.1 mm/min, 3 slices/wire, 95% yield over one run. Slicing of 15-cm-dia ingots was demonstrated but was not considered successful.

During the last few months of the program, emphasis was placed on the plating of wirepacks and theoretical calculations to optimize contact lengths.

Shaped-Sheet Technology

Mobil Tyco Solar Energy Corp. (Edge-Defined Film-Fed Growth--EFG)

The EFG technique is based on feeding molten silicon through a slotted die. In this technique, the shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from a material that is wetted by molten silicon (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 4.5 cm/min and a width of 10.0 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic and theoretical analysis of ribbon thermal and stress conditions. The EFG contract was terminated in December 1981 by FSA directive.

Activities in this period centered on Machines No. 17 and 18. In Machine No. 17, a new gas-control system was used to reduce the argon ambient pressure in the main zone. Ten runs were made with this new system to evaluate different cartridge configurations in improving material quality and to acquire temperature profile data for thermal stress and buckling studies. The ribbon dimensions are typically 10 cm in width, 10 mils thick and grown 3 to 6 cm/min. Eight runs were made with Machine No. 18 to evaluate various die configurations, phase heater thermal profiles, cold-shoe positioning and thermal stability of the furnace. The 10-cm-wide, 14-mil-thick ribbons were grown typically at rates of 2 to 2.5 cm/min.

In work supported by Mobil Tyco, several EFG cells, each approximately 50 cm² in area, displayed average efficiencies of 11.1% AM1. The ribbons used for these cells were 10 cm wide and grown at 3.6 cm/min. Fabrication of Machine No. 21, the multiple ribbon experimental sheet growth unit (ESGU), now funded internally, is progressing to the final check-out stages.

ADVANCED MATERIALS RESEARCH TASK

Activities in 1982 have centered on negotiations for Mobil Tyco to conduct research in high-speed ribbon growth.

Westinghouse Electric Corp. (Dendritic Web Growth--Web)

Dendritic web is a thin, wide-ribbon form of single-crystal silicon produced directly from the silicon melt. "Dendritic" refers to the two wirelike supporting dendrites on each side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film between the bounding dendrites. Dendritic web is particularly suited for fabrication into solar cells for a number of reasons, including the high efficiency of the cells in arrays and the cost-effective conversion of raw silicon into substrates.

A set of three computer models that were developed to characterize critical elements of Si web growth was used successfully to define a growth system configuration that provides reduced thermal stress and increased area throughput rate. These models were then used to predict and define for the first time a new and better system configuration that was subsequently built and tested; the results verified the model predictions. This first configuration has grown web with lower thermally generated stress than has any configuration developed heretofore by solely experimental methods rather than computer models.

The models (1) predict the critical stress at which buckling will occur within a Si ribbon of specific width and thickness, (2) relate the thermally generated stress and the temperature distribution for a Si ribbon, and (3) predict the Si ribbon temperature distribution that will be generated by a specific thermal geometry and dimensions within the growth system. These models had previously been verified and refined by comparison with test data obtained using existing, experimentally developed web growth configurations.

It was found that (3) above was not sufficiently definitive to provide the desired growth improvement. A more definitive model was developed, and it was verified by comparison with known performance of existing and well-characterized web growth configurations. This model will be used to develop the next web growth configurations to be defined by computer models.

A set of shields was designed and fabricated, incorporating constant-width (3 cm) control and low-stress features. The configuration is undergoing tests in an experimental web growth machine equipped with closed-loop control and melt replenishment to provide constant melt level during web growth. Constant width of growth has been attained, and fine-tuning of the system is expected to demonstrate semiautomatic, steady-state web growth soon.

ADVANCED MATERIALS RESEARCH TASK

Supporting Studies

Solarelectronics, Inc. (Investigation of the Hydrochlorination of Silicon Tetrachloride)

A research and development program is being carried out to study the hydrochlorination of silicon tetrachloride (STC) and metallurgical-grade silicon to trichlorosilane (TCS) in a 2-in.-dia reactor:



The effect of pressure and temperature on the hydrochlorination reaction was studied. The results clearly showed that higher reaction pressure produces a higher TCS conversion but at a slower reaction rate. The equilibrium conversion of TCS is about 21% at 73 psig; 35% is achievable at 300 psig under the same conditions. The effect of temperature on the hydrochlorination reaction was studied at 73 psig and at a H_2/STC feed ratio of 2.8. Higher reaction temperature (500°C vs 450°C) produces both a higher reaction rate and a higher conversion of TCS. The investigation is under way to systematically study hydrochlorination reaction at pressures of 14.7, 100, 150, 200, 300, and 500 psig; temperatures of 350°, 400°, 450° and 500°C; and H_2/STC mole feed ratios of 1.0, 2.0, 2.8, 4.0, and 5.0.

Experiments were also conducted on a corrosion study to evaluate material of construction for a hydrochlorination reactor. Materials tested were Type 304 stainless steel, carbon steel, Incoloy 800H, Alloy 400, Hastelloy B-2, nickel, and copper. These samples were mounted inside the 2-in.-dia hydrochlorination reactor tube. The corrosion test was conducted for 100 h at 500°C, 300 psig, and a H_2/STC feed ratio of 2.0. It was found that in every case the weight of the corrosion coupon was increased instead of decreased, as expected, from corrosion. The weight gain by the test samples is due to the deposition of silicon from the hydrochlorination reaction. The deposited silicon penetrates the metal alloy surface to form a silicide film that prevents further corrosion.

The Incoloy 800H corrosion coupons were studied by a scanning electron microscope to investigate the corrosion mechanism. The composition of the silicide film deposited on the coupon was analyzed by the X-ray microprobe and the EDAX analyzer. SEM photographs indicated a 100-micrometer-thick silicide film deposited on the coupon. The EDAX analysis at the four different areas of the test sample shows that the bulk of the silicide film has the atomic composition of 40% to 50% Si. This corresponds to the nickel-silicon phases of Ni_3Si_2 and NiSi .

Texas Research and Engineering Institute (Technology and Economic Analysis)

Chemical engineering and cost analyses for a 1000-MT/yr plant for the dichlorosilane (DCS) process (being developed under the contract with Hemlock Semiconductor Corp.) are being conducted by the Texas Research and Engineering Institute. The engineering design of the second distillation column, which is for the separation of trichlorosilane (TCS) from silicon tetrachloride, and the initial design of the third distillation column, which is for the separation of

ADVANCED MATERIALS RESEARCH TASK

DCS from TCS, were completed. Lists of raw material and utility requirements were developed. Work on base-case conditions, reaction, chemistry, process flow diagram, material balance, and energy balance have been completed. Cost analysis is under way.

University of Illinois, Chicago (Study of Abrasive-Wear Rate of Silicon)

The purpose of this study is to develop an understanding of the abrasion and wear of silicon through modification of the surface properties by interaction with fluids. The positive effect of chemical environment on the abrasive wear rate of silicon, if any, would be useful in improving ingot wafering and reducing surface damage to silicon wafers.

Silicon was abraded at room temperature in the presence of acetone, absolute ethanol and water by a pyramidal diamond and the groove depth was measured as a function of normal force on the diamond and the absorbed fluids. The wear rate for silicon was found to vary in a ratio of 1:2:3 for water, ethanol and acetone, respectively, with a constant normal force.

In-House Activities

Crystal Growth

Siltec Corp.'s Czochralski ESGU has been delivered to JPL and is being installed for research on crystal growth. Initial test runs are scheduled in the third quarter of FY82.

A joint technical brief with IBM was written and filed for a patent. The technique consists of varying the crucible rotation during directional solidification. This results in better stirring of melt and promotes favorable conditions for single-crystal or large-sized grain growth.

More Czochralski bicrystals have been grown for the study of boundaries between grains of various relative orientations. The study of growth-zone thermal condition and its effect upon the growth of shaped Czochralski ingots continues.

Surface Photovoltage Technique

The surface photovoltage (SPV) technique, used to determine the minority carrier diffusion length in silicon, was updated during this period. Important to the technique is an accurate knowledge of the optical absorption coefficient in the silicon. The absorption coefficients in Cz, web, and HEM were measured in the wave length interval $0.8 \leq \lambda \leq 1.0 \mu\text{m}$, which is the region of interest for the SPV measurements. Minority carrier diffusion lengths computed using the present absorption coefficients are approximately 16% greater than those using the recommended ASTM standard values. A paper describing this work has been submitted to the Journal of Applied Physics.

ADVANCED MATERIALS RESEARCH TASK

Fluidized-Bed Reactor Study

The 2-in.-dia fluidized-bed reactor (FBR) experiment in defining the operating window and Si deposition kinetics were completed. Testing temperatures ranged from 650° to 750°C while silane concentration varied from 20% to 65%, limited by heating capacity of the existing setup. Even with a high silane concentration of 65%, effluent dust collection can be kept below 10% without bed agglomeration. A high deposition rate of 0.5 kg/h of Si has been obtained with 50% silane in a 2-in. FBR. These observations, plus scanning electron microscope evidence, show that in addition to the chemical vapor deposition phenomenon the fluidized-bed seed particles can scavenge homogeneous fines onto the growing surface. The combination effect results in fast-growth, coherent, free-flowing particles. The operating window was also identified in the 2-in. FBR: temperature within 650° to 750°C fluidization quality indicated by U/U_{mf} between 3 and 6, bed height $L/D \leq 3$. The basic mechanism, kinetic data, and operation guidelines identified in JPL 2-in. FBR are expected to benefit the economics of the fluidized-bed Si deposition approach greatly.

The 6-in.-dia FBR system was designed, fabricated and constructed at JPL. It has been checked out in terms of leak, fluidization and heating tests. A technical review was conducted with Task consultants. During the initial experiment (<400°C, to prevent plugging of distributor) with silane, which has a higher heat capacity than previously tested hydrogen, a desirable temperature profile to keep the lower part of the bed hot and the distributor cool cannot be maintained. Heater and distributor cooling are under redesign and modification.

Fracture and Properties Modification of Silicon

Fracture toughness (K_{IC}) of Semix polycrystalline silicon material was measured at room temperature in laboratory environment by microindentation of a bending bar. The test result indicated that the K_{IC} values of Semix have an average of 0.78 MN/W^{3/2} on a slab surface, which is consistent with the data reported previously for single crystal of 0.82 to 0.93 MN/W^{3/2} and for Silso Wacker material of 0.80 to 0.87 MN/W^{3/2}.

In order to study photon-electron interaction on the surface properties of silicon, a double torsion test jig was built. Because of availability, HEM polycrystal samples are being prepared for the preliminary test. Single-crystal samples in several crystalline orientations are being procured for this study.

Multiblade Slurry Wafering Research and Development

Continuous wafering of polycrystalline silicon material for more than 24 hours was demonstrated using a JPL-developed water-base abrasive slurry system and instrumented multiblade saw. This new, low-cost abrasive slurry system has provided satisfactory cutting action and wafer surface finish over several wafering runs.

Two new-technology items were submitted to the JPL-California Institute of Technology and Patents Office: "Development of a Water-Base Abrasive Slurry

ADVANCED MATERIALS RESEARCH TASK

for Use in the Slicing of Silicon Material," the result of silicon wafering research and development conducted by T. O'Donnell, C. Chen, and W. Hite using an instrumented multiblade slurry saw, and "A Modified Multiblade Slurry Saw for Load-Controlled Wafering of Silicon," a result of in-house modifications and redesign of a Varian multiblade slurry saw in support of advanced research into new/alternative expendable materials for this technology, by T. O'Donnell and W. Hite.

A procurement for specially designed diamond-coated high-carbon-steel blades was initiated with Diamotec, Torrance, California.

Material Property Modification:

An electromechanical softening effect in semiconductor materials has been described in a concept paper. A preliminary test plan has been developed to verify the electromechanical softening effect and to characterize the mechanism by which these materials are softened when exposed to surface loading and the simultaneous presence of a small potential (less than 10 V).

Device and Measurements Research Task

INTRODUCTION

The objective of this task is to identify and implement research and development activities in the photovoltaic device and measurements area to meet the near-term and long-term objectives of the FSA Project. Task activities encompass research in device physics, device structure, material-device property interaction, and measurement techniques for physical, chemical and electrical evaluation of devices and materials.

Technical Approach, Organization and Coordination

To meet FSA objectives, efforts are now directed toward characterization of various silicon-sheet materials, material-device property interaction investigation and measurement techniques. The program of the Task is structured accordingly.

Ongoing research contracts awarded for material and device evaluation are listed in Table 2.

The program of the Task also includes JPL in-house activities to conduct basic research in materials and devices characterization to support contractor needs and other Tasks of the Photovoltaic Components Research Area.

SUMMARY OF PROGRESS

C.T. Sah Associates: Completed the contract on the effects of impurities and defects on the properties of silicon material and on the performance of silicon solar cells. The final report, "Study of the Effects of Impurities on The Properties of Silicon Material and Performance of Silicon Solar Cells," was issued. It contains the results of work performed after publication of the Fourth Annual Report, dated March 1981. A theoretical analysis of the effects of defects across the back-surface-field junction on the performance of high-efficiency, thin solar cells is included; in this analysis a developed perimeter device model for the three-dimensional effects is used. In addition, a new theory, capable of distinguishing an acceptor-like deep level from a donor-like deep level using the measured value of the thermal emission and capture cross-sections, is described. Using the measured thermal emission and capture cross-sections, this theory can also provide information concerning the magnitude of the lattice distortion around an impurity atom before and after the capture or emission of an electron or a hole at the impurity center.

Westinghouse Electric Corp.: Completed the contract on defining the effects of impurities and processing on solar cell performance. The following is a summary of the entire effort from its inception in October 1975:

DEVICE AND MEASUREMENTS RESEARCH TASK

Table 2. Device and Measurements Research Task Contracts

Contractor	Research Area
Applied Solar Energy Corp. City of Industry, CA JPL Contract NO. 955089	Cell fabrication and silicon-sheet evaluation
Cornell Univerity Ithaca, NY JPL Contact No. 954852	Characterization of silicon-sheet properties
Materials Research, Inc. Centerville, UT JPL Contact No. 957977	Quantitative analysis of defects and impurity evaluation technique
University of California, Los Angeles Los Angeles, CA JPL Contract NO. 956233	High-efficiency solar-cell structures by molecular-beam epitaxy
C.T. Sah Associates Urbana, IL JPL Contact No. 954685	Effects of impurities on solar-cell performance
Westinghouse R&D Center Pittsburgh, PA JPL Contract No. 954331	Definition of purity requirement in silicon

The effects of various metallic impurities introduced into silicon ingots and into silicon ribbons were studied. The solar-cell data indicate that impurity-induced performance loss is caused primarily by a reduction in base diffusion length. An analytical model was developed.

Polycrystalline ingot studies indicate that cell behavior is species-sensitive and that a fraction of the impurities are segregated to the grain boundaries.

HCl and POCl_3 gettering improve the performance of cells containing iron, chromium, and titanium. Similar behavior was observed for the polycrystalline devices. Argon ion-implant damage does not significantly enhance gettering. The efficiencies of cells fabricated on impurity-doped wafers are lower when the junction is formed by ion implantation. Solar-grade silicon feedstock impurity concentrations will have to be below one part per million for some elements or 100 parts per million for more benign impurities, depending on tolerable cell efficiency, crystal growth method, melt replenishment strategy and cell process sequence.

The final report, "Effect of Impurities and Processing on Silicon Solar Cells," was issued in February 1982.

DEVICE AND MEASUREMENTS RESEARCH TASK

Applied Solar Energy Corp. (ASEC): Proper assessment of potential low-cost silicon-sheet materials requires the fabrication and testing of solar cells using reproducible and reliable processes and standardized measurement techniques. Wide variations exist, however, in the capability of sheet-growth organizations to fabricate and evaluate photovoltaic devices. It is therefore logical and essential that the various forms of low-cost silicon sheet be evaluated impartially in solar-cell-manufacturing environments with well-established techniques and standards. ASEC has been retained to meet this need.

Materials Research, Inc.: The current MRI sheet defect-structure assessment effort includes a correlation of impurity distributions with defect structures in various sheet materials obtained from the ingot and shaped-sheet manufacturers.

Cornell University: Cornell has conducted Rutherford backscattering experiments on front and back surfaces of web cells fabricated by ASEC. The results revealed that significant amounts of molybdenum are present in the diffused layer as well as in the base material.

The structural arrangement and the electrical activity of dislocations at or close to the central twin plane in processed web material was studied by electron-beam induced-current (EBIC) microscopy on a shallow-bevel specimen. The majority of the dislocations in the twin plane are regularly spaced and mostly straight arrays of dislocation of like sign, accommodating a tilt component. Dislocation density in the twin plane is high and the dislocations are effective recombination centers. Inspection of straight sections under higher magnification shows that the electrical activity varies along the dislocation, possibly due to precipitates (transmission electron microscopy will be carried out after completion of EBIC to clarify this point). Temperature-dependent EBIC work is being carried out in order to determine the electronic energy levels associated with the various sections.

University of California, Los Angeles: A contract, "Silicon Sheet With Molecular Beam Epitaxy (MBE) for High-Efficiency Solar Cells," was awarded to University of California, Los Angeles. In this effort, various silicon layers will be grown on JPL-provided silicon substrate using MBE. These layers will be evaluated for structural properties and electrical performance, and solar-cell structures will be fabricated for diagnosis to enhance open-circuit voltage and efficiency.

JPL in-house research included structural and electrical characterization of grain boundaries in polycrystalline and JPL-grown silicon bicrystals, Zeeman atomic absorption and secondary ion mass spectroscopy measurements on Semix material, and analysis of electrically active impurities in silicon by using thermally stimulated capacitance measurements.

Environmental Isolation Task

INTRODUCTION

The objective of the Environmental Isolation Task is the development and qualification of the total encapsulation system required to protect the active optical and electrical elements of a photovoltaic array from the effects of the field environment. The most difficult technical problem has been the development of high-transparency materials for the photoactive side of the module that meet the Project's low-cost and 20-year-life objectives. The approach to the objective includes a combination of contractor and JPL in-house efforts, which can be divided into two technical areas:

- (1) Materials and Process Research. This effort includes all of the work necessary to develop, demonstrate, and qualify one or more encapsulation systems to meet FSA cost and performance goals. It includes the testing of off-the-shelf materials, formulation and testing of new and modified materials, identification of automated processes to handle these materials during formulation and fabrication of modules, and systems analysis and testing to develop optimal module designs.
- (2) Material Durability and Life Testing. This work is directed toward the attainment of the FSA 20-year-minimum life goal for modules. It includes research aimed at the development of a life-prediction method applicable to terrestrial photovoltaic modules, and validation of that method by specific application to photovoltaic demonstration sites. Material degradation studies are being conducted to determine failure modes and mechanisms. This effort supports both the materials and process development work and the life-prediction model development.

SUMMARY OF PROGRESS

ISOLATION MATERIALS AND PROCESS RESEARCH

Additional investigation of ethylene methyl acrylate (EMA) has been pursued by direct contact with the manufacturer, Gulf Oil Chemicals Co. During initial meetings, Gulf representatives were enthusiastic about the potential use of EMA as an encapsulation pottant, and would consider marketing the product for such applications if accepted by the photovoltaic industry. Gulf further agreed to discuss their providing technical assistance and information that would aid in advancing the development of this material for PV applications.

Peroxide curing agents that achieve faster EVA cure at lower temperatures were identified and tested by Springborn. The experimental agents are Lupersol 331-80B and Lupersol 99. Lupersol 101, the agent currently used, requires about 20 minutes at 150°C, while Lupersol 331-80B achieves the same results in 10 minutes at 130°C. Lupersol 99 was also found to speed EVA cure, and studies are now being performed to determine specific time and temperature.

ENVIRONMENTAL ISOLATION TASK

The chemistries of these curing agents will also be determined, and attempts will be made to define chemical trends that may enable selection by chemistry of curing agents having even faster and lower-temperature characteristics.

Further contacts were made with Inland Steel Co. (IS), manufacturer of "MartINsite," a mild steel with the highest strength-to-cost ratio of any commercial mild steel product. IS agreed to provide support to Springborn in identifying corrosion prevention techniques, and in development of ribbed stiffening methods for flat steel plates. IS engineers said that the thinnest steel plate that would suffice for rib reinforcing is 0.008 in.; thinner material has the mechanical qualities of flexible metal foils.

IS also pointed out that certain material width and thickness restrictions must be considered. Low-strength mild-steel products less than 0.015 in. thick are limited to 40-in. widths, while all high-strength mild-steel products are thicker than 0.015 in. and are limited to 35-in. width. Knowledge of such constraints is vital to the design of large-area modules.

In the area of outdoor soiling behavior, two candidate surface-treatment materials were tested. They are being evaluated on Sunadex glass and on two UV screening plastic films: Acrylar from 3M Co., and Tedlar from Du Pont Co. The candidate fluorinated materials are L1668, manufactured by 3M Co., and perfluorodecanoic acid (with Dow Corning Corp. primer), and tests have shown that the glass and two plastic films so treated not only are cleaner than untreated control samples, but also exceed the performance of all other non-fluorinated materials.

Soiling resistance tests showed that the soil accumulation after five months on the untreated Sunadex control resulted in a 3% loss of short-circuit current (I_{sc}) from a standard cell; the L1668-treated Sunadex resulted in only a 0.5% loss in I_{sc} from the same cell. In general, L1668 performed better on glass than on the plastic films, and the perfluorodecanoic acid performed better on the plastic films than on glass.

Adhesives and Primers Research

E. Plueddemann of Dow Corning has continued his work in this area, and has developed an experimental primer system for bonding poly-n-butyl acrylate to glass. This primer is now being supplied to the seven PV manufacturers who are evaluating the Springborn poly-n-butyl casting syrup. Additional work was performed on developing primer systems for Acrylar films, and on further development of polyurethane casting pottant.

UV Absorbers

Synthesis of 2(2-hydroxy-5-isopropenyl)2H-benzotriazole (2H5P) was accomplished, as well as a more practical synthesis of 2(2-hydroxy-5-vinylphenyl)2H-benzotriazole(2H5V). Copolymerization of 2H5P was completed but not the homopolymerization.

The previously reported UV absorbing compounds, 2(2-hydroxy-5-isopropenyl) (2H5P) and 2(2-hydroxy-5-vinylphenyl)2H-benzotriazole(2H5V), were

ENVIRONMENTAL ISOLATION TASK

studied using ^{13}C NMR spectra. Observed chemical shift data were compared with predicted shift data in hopes of correlating UV-induced molecular motion of the phenol ring with observed UV absorption spectra. This would assist in the understanding and prediction of the stability of polymers containing chemically attached UV stabilizers.

Two additional derivatives of the UV absorber 2(2-hydroxyphenyl)-2H-benzotriazole were successfully synthesized. They can be permanently incorporated into PV encapsulation materials in support of the goal of the Environmental Isolation Task to develop encapsulation systems that retain their protective function for 20 years or more. The derivatives are: 2(2,4-dihydroxyphenyl) 2 H-benzotriazole (2,4DH) and 2(2,4,6-trihydroxyphenyl) 2H-benzotriazole (2,4,6TH). Condensation of the diazonium salt of o-nitroaniline with resorcinol followed by reductive ring closure led to the synthesis of the 2,4DH, which was followed by purification and characterization. The same reaction sequence substituting phloroglucinol for resorcinol should lead to 2,4,6TH.

In order to establish a theoretical foundation to predict and tailor the incorporation into the backbone of vinyl polymers of the already characterized and purified UV absorber, 2(2-hydroxy-5-isopropenylphenyl) 2H-benzotriazole (2H5P), a systemic study of its copolymerization rate was initiated. Plans called for synthesizing enough 2H5P during the next month for copolymerization to styrene (ST) and methyl methacrylate (MMA).

In continuing their efforts to find derivatives of a stable UV absorber that can be permanently incorporated into PV encapsulation materials, the University of Massachusetts has synthesized two more compounds: 2(2,4-dihydroxyphenyl)2H-bisbenzotriazole (2,4-DHB) and 2(2,4,6-trihydroxyphenyl) 2H-bisbenzotriazole (2,4,6-THB). These compounds are expected to have good UV-stabilizing efficiency. Samples of both were sent to JPL for photophysical studies.

Other efforts were focused on the synthesis and characterization of the UV absorber monobenzotriazole-substituted resorcinol (2, 4-DHB). An attempt was also made to improve the yield of dibenzotriazole-substituted phloroglucinol.

Negotiations are now in progress to extend our contract with the University of Massachusetts, with the final report due at the end of the extension period.

Module Design and Verification

Spectrolab, Inc., has advanced into the experimental evaluation of specific designs, part of the Phase II work.

As a part of their Phase II activities, Spectrolab was to fabricate up to 10 4-ft-square modules of an optimized design identified by them to have potentially the lowest life-cycle energy cost. The identified design is a substrate module using ribbed 1/8-in. thick hardboard as the structural substrate. One of the requirements of optimization is that the fabricated modules must pass the JPL module qualification tests.

ENVIRONMENTAL ISOLATION TASK

It was planned to fabricate the modules by conventional vacuum-bag lamination, using EVA as the pottant, but dry-out shrinkage of the wood prevented this, and two alternatives were explored. The first was a two-step process wherein the solar-cell string was vacuum-laminated in a composite of a white plastic film, EVA, and a clean UV screen plastic film. This composite was then bonded to the wooden substrate, preferably with a room-temperature adhesive. The second fabrication option was to cast rather than laminate, using the recently identified polyurethane casting resin from Development Associates.

Prototype wooden-substrate modules fabricated by a two-step, vacuum-bag lamination process were successfully made, by laminating solar-cell strings in EVA with front and back layers of clear UV-screening Acrylar in one version, and clear UV-screening Tedlar in another version. The flat laminated packages were bonded to the wooden substrate using a room-temperature-curing polyurethane adhesive. A white background was achieved by painting the wood with a white paint, before attaching the laminated package.

The module fabricated by Development Associates, Inc. (DAI) indicated that casting cannot be dismissed as a fabrication option. Therefore, it was decided that two of the 10 Phase II 4-ft square wood modules would be fabricated by a casting process, using a DAI polyurethane pottant system, and the other eight modules would be fabricated by the lamination process using EVA pottant.

Spectrolab will now team with JPL to construct a 4-ft-square laminator at the FSA Foothill facility. This should be completed late in April or early in May of 1982.

The basic contents of Spectrolab's Phase II Report were presented informally to the Environmental Isolation Task at a meeting held on February 18, 1982. At this meeting preliminary discussions were held on the technical plan of work for a proposed two-year contract extension. The contract add-on will enable Spectrolab to refine its design analysis models and use them to identify and establish priorities for those material and system properties that are most sensitive to weathering. The sensitivities (rates of change) and the upper and lower property bounds will be established and used to guide future research on accelerated exposure testing and polymer stabilization.

Four computer models are being developed at Spectrolab to simulate module response in the areas of electrical isolation, structural integrity, optical properties, and thermal properties (module operating temperature). Phase II work has essentially validated the thermal model and partially validated the others. The model in least agreement with experimental results is that for predicting solar-cell stresses from thermal stresses due to thermal-expansion differences. It is believed, however, that Phase II experimental validation techniques, rather than the computer model, is the source of the discrepancies.

Advanced Module Design

Science Applications, Inc. (SAI) was funded in March of 1982 to do experiments aimed at demonstrating increases in solar-cell power output by light-trapping techniques. Power enhancement by light trapping involves the thickness and the index of refraction of the transparent layers of encapsulation

ENVIRONMENTAL ISOLATION TASK

materials on the sun side of the solar cells. SAI will design the modules, which will be fabricated by Springborn. SAI will then carry out experiments on power measurements.

Ion-Plated Coatings

Illinois Tool Works (ITW) has finally succeeded in depositing metallization with an ohmic contact on the p back surface of n-on-p solar cells, although not on a routine basis. Ohmic contact is defined as achieving a resistance of equal to or less than 0.160 ohms-cm^2 .

The first breakthrough came from efforts to metallize with aluminum on the back surfaces of n-on-p solar cells with differing boron concentrations. Better ohmic contact was achieved on the cell having the higher boron concentration. The second improvement came from using an alloy of aluminum and titanium, recommended by W.E. Taylor of Spectrolab, and thereafter ohmic contact was finally achieved using aluminum/titanium alloys that were doped with boron. The deposited metallization on the back surface required no firing.

Incorporating low-level concentrations ($<1\%$) of boron in an alloy of aluminum and titanium has enabled ITW to achieve ohmic contact on the back surface of p-on-n solar cells without firing. However, they have been unable to do this repeatedly. It is believed that impact energy associated with the incoming ion stream causes damage to the crystalline microstructure of the back surface. A literature search has found that boron can function to anneal the crystalline structure of silicon, thus acting in some way to duplicate chemically the action of high-temperature annealing. It is further speculated that boron present in the bulk of the back-side metallization layer has no annealing effect. Apparently it is only effective at some concentration level that initially reaches the surface and that will be localized in the interface between the cell and the metal layer. In addition, the generation of the ion stream in the ITW process can cause fractionation of the metal alloy, causing the departing ion stream to have a composition different from that of the starting solid alloy. ITW is carrying out two technical actions: (1) depth profiling by Auger analysis of the boron concentration in the metal layers on a good and a poor cell, and (2) investigating the fractionation process to regulate boron concentration in the departing ion stream.

Depth-profiling Auger analysis of the ion-plated aluminum-titanium metallization on the back surface of the n-on-p solar cells has, surprisingly, revealed the presence of copper in the cell-metallization interface for cells with good ohmic back-side contact. No copper has been found for those ion-plated cells having poor ohmic back-side contact. It was speculated that boron in the metallization was the element affecting ohmic quality; this depth-profiling analysis was intended to provide an understanding of boron's role. Copper, and not boron, is apparently the significant element, and further analysis will be performed to determine its origin and role in the process.

ENVIRONMENTAL ISOLATION TASK

MATERIAL DURABILITY AND LIFE TESTING

Degradation Computer Modeling

Studies at the University of Toronto have shown that there is an induction period preceding the autocatalytic photooxidation of polymeric FSA materials during which there are no significant changes in the structure of the polymer. Efforts have been aimed at gaining a better understanding of the influencing factors, so that this phase may be extended as long as possible.

The effects of varying the concentrations of initiators such as ketone or peroxides has been studied and it was found that there is only a narrow window within which the simulated behavior is representative of the true reaction scheme. Careful evaluation has shown that there may be an intrinsic effect or limitation within the existing numerical integration procedure. The present method is dependent on the rate of change of the concentration terms and allows for variation in step length as the integration proceeds.

As it is now programmed, the choice of the step length is made just before iteration and is internal to the program. Once the integration begins, values are unrelated to the initial starting conditions and any set parameters. To better understand this problem, a grasp of the error underflow and significance will be required.

Work will continue to understand or solve this problem as it may serve to underscore the known importance of adding some type of stabilizer to almost any polymeric material if a lifetime of several years is to be expected. Knowledge of the effects of such impurity concentrations is vital in any polymer life prediction model, as these impurities are common in commercial preparations.

Interface Degradation Corrosion Diagnostics and Modeling

Rockwell Science Center is continuing its investigation of corrosion-inhibiting properties of the primer system developed by Dow Corning, and results on EVA bonded to primed mild steel show that this system does provide corrosion protection. Tests on other metals, including copper and aluminum, will be performed.

AC impedance techniques have been used to monitor the aging behavior of test modules exposed to the Battelle Accelerated Test. Artificial aging was performed at JPL and the impedance tests were performed at Rockwell. This technique appears to be sensitive means of detecting early aging events in functional modules. The Rockwell annual report was received and reviewed. Also, a statement of work for a proposed two-year contract extension was submitted to Rockwell; they responded by presenting a technical plan to JPL in March 1982.

Photodegradation of Polymers

The design and installation of the UV Qualification Test Chamber was completed after safety review and approval during November of 1981. In February 1982 a report titled "Photothermal Characterization of Encapsulant Materials for Photovoltaic Modules" was completed and submitted for publication.

ENVIRONMENTAL ISOLATION TASK

Response of fundamental polymer mechanical properties as a function of polymer preparation were studied. Crosslinking densities of EVA samples cured at 280°F in air for various periods of time were measured, and results were as follows:

<u>Cure Time (min)</u>	<u>Crosslinking Density</u>
10	0.4634×10^{-6}
30	2.722×10^{-6}
60	4.422×10^{-6}
90	7.003×10^{-6}
135	11.850×10^{-6}

These results will be used to support life prediction and module encapsulant durability studies.

Continuous aging of Acrylar films (3M-PMMA) inside the Control Environment Reactor (CER) was completed, with accumulated aging time reaching 200 days. Samples were subjected to 4 suns of irradiation at 50°C and 2 hours of simulated rain in every 24-hour period. Data indicated a gradual decrease in UV screening capability after an induction period of 60 days. Approximately 50% of the UV screen was lost after 200 days of aging. Chemical analysis also showed separability of the UV screen from the parent polymer. Apparently the screening is not chemically incorporated as was first believed.

Construction of a second CER capable of maintaining higher aging temperatures was completed and characterization was performed. Aging temperatures as high as 130°C and photon flux equivalent to 10 suns have been achieved.

Evaluation of a novel diagnostic technique for early detection of photooxidation that involves detection of a hydroxyl functional group (one of the products of photooxidation) was initiated. Feasibility experiments will be carried out at the Center for Laser Studies at the University of Southern California.

Degradation of Acrylics

Analysis and correlation of data is continuing at Case Western Reserve University. Samples of poly-n-butyl acrylate were kept under exposure to UV light in the QUV test chamber for analysis to determine their long-term UV resistance, to measure the validity of predictions made on the basis of short-term exposure data. Refinement of the data analysis method using FTIR with assigned baseline for product analysis is being completed.

ENVIRONMENTAL ISOLATION TASK

Two papers based on the work performed were presented at the National ACS meeting in Las Vegas, Nevada in March 1982:

- (1) "Effects of Photodegradation on the Sorption and Transport of Water in Polymers," by C.E. Rogers.
- (2) "Photodegradation of Poly-n-Butyl Acrylate" by H.R. Dickinson, C.E. Rogers and R. Simha.

MODULE FIELD TESTING

Minimodule Field Testing (JPL)

All of the Point Vicente, California minimodules and two-cell submodules have undergone I-V response testing using the JPL large-area pulsed solar simulator (LAPSS) facility. Measurements before and after storage indicated changes in power output of some modules of up to several percentage points. These modules were returned to the Point Vicente site after 270 days of protected storage while facilities modifications were under way. Four designs (glass/EVA/Mylar, glass/EVA/Acmetite, glass/polyurethane and glass/polyurethane/Acmetite) were observed to "heal" or increase in power output. Four designs (glass/EVA/aluminum foil, Korad/EVA/galvanized steel, Tedlar/EVA/Acmetite/glass, reinforced concrete and glass/electrostatically bonded cells/white EVA/Acmetite) appeared stable, showing very little average increase or decrease in power output. Only one minimodule design (Korad/EVA/SuperDorlux) decreased in power output.

Other events:

- (1) Minimodules from the Goldstone field test site were retrieved and I-V curve tests were performed.
- (2) Humidity testing of all minimodule designs was completed in February 1982.
- (3) The final report on the evaluation of the Battelle Accelerated Test Plan was completed and submitted for Task Review in March 1982.
- (4) Three Photowatt International, Inc., minimodules using Quinn Q626/621 polyurethane as a pottant have darkened to a bronze color. This change has not been observed at either the JPL or the Pt. Vicente sites. The discoloration has not, however, affected power output levels in these modules.
- (5) An interim report summarizing the results of the minimodule field testing was prepared, and significant results were presented at the 20th Project Integration Meeting.

CELL AND MODULE FORMATION RESEARCH AREA

INTRODUCTION

The objective of the Cell and Module Formation Research Area is to identify, to assess, and to conduct research on methods for the formation of solar modules, and to make these technologies available to the photovoltaic industrial community.

For convenience, process development is grouped into four categories: surface preparation, junction formation, metallization, and module completion.

SUMMARY OF PROGRESS

The Area's effort on Module Experimental Process Development Units (MEPSDU) has been modified to involve only the research aspects of the contractors' prior activities. However, both Solarex Corp. and Westinghouse Electric Corp. were completing specific MEPSDU tasks at the start of this reporting period; these accomplishments are reported under their appropriate process category headings.

Three requests for proposals (RFPs) were issued and the resulting proposals were received and evaluated by JPL. In accordance with DOE guidelines two of the three activities, module assembly and effluent treatment, have been postponed. The third activity, metallization, was pursued and a contract was awarded to Spectrolab, Inc. for the development of a thick-film metallization system based upon molybdenum, tin, and titanium hydride.

Surface Preparation

Photowatt International, Inc., is working with silicon nitride (Si_3N_4) antireflection (AR) coatings, which allow a metallization system (thick-film) to penetrate during firing. The advantage of this concept is that no patterning of the AR coating is required, either before or after metallization. The coating offers optical enhancement right up to the metal edge with no etch window or masked space tolerance. Of primary interest is the fact that the elimination of a patterning step increases yields and reduces costs.

Solarex Corp. has completed the development of its ion-milling process for junction-edge cleanup and of its glass-bead blasting process for cleanup of cell back surfaces after firing in the aluminum.

Junction Formation

Spire Corp. has completed the design of its non-mass-analyzed (NMA) ion implantation machine. It has separated the ion species being emitted from the NMA source and discovered that an acceptable level of contamination exists. The design includes an electrostatic beam defocusing technique that puts a "dog-leg" offset into the beam path, which improves uniformity and reduces the

CELL AND MODULE FORMATION RESEARCH AREA

height of the machine. Cells made by the NMA source are as good as control cells made by conventional ion implanters.

Westinghouse is applying a research-oriented effort toward improvements in junction formation on silicon web material, including dopants applied as a liquid and at ion implantation. Both methods apply the junction to the desired side only, obviating masking or removal of the unwanted junction surface.

JPL in-house junction-formation work is directed toward pulsed plasma epitaxy. This process involves the ablation of the surface of the source material by ion plasma pulses. It is an extension of NASA technology (as is the NMA activity) that has been utilized for pulse thrusters on space vehicles. It is hoped that this process will allow heavier, deeper junctions than are practical by ion implantation.

Metallization

Bernd Ross Associates have uncovered a relationship between metal (thick-film) adhesion and sintering in a hydrogen environment. It is believed that the silicon surface hydrogenates and as a result is less acceptant of metal coatings. When fired in carbon monoxide as a reducing atmosphere, the metal adheres well.

Photowatt has succeeded in formulating a thick-film, nickel-based metal paste that penetrates the AR coating and bonds well to the silicon. The metal layer thus formed has excessive electrical resistance; it was intended that the surface be built up by copper plating. All plating solutions tried have destroyed the metal layer bond to the silicon. Photowatt is working with fritless metal inks and other metal systems and/or additives in order to solve this problem.

University of Pennsylvania has completed its assessment of metallization design optimization methods. The previous conclusion that rectangular grid pattern designs are optimal has been modified as a result of a detailed analysis of the Westinghouse fan-style design. After individual optimization, both designs perform comparably. This is not to be taken, however, as an indication that grid pattern design is insensitive to optimization.

Solarex reports that although its wave-soldering process successfully builds up electroless nickel plating on one cell surface, when applied to the second surface the first surface is degraded. There is no indication that it matters which surface, front or back, is processed first.

Module Completion

Westinghouse modules have successfully completed environmental testing at JPL. The glass-superstrate design has proven to be humidity-resistant and capable of withstanding specific temperature-cycling and hailstone-impact tests. The rolling-spot ultrasonic bonding technique has advanced from a

CELL AND MODULE FORMATION RESEARCH AREA

successfully demonstrated concept to a completed and operating fabrication machine. This work is completed.

JPL in-house laboratory work has indicated that adhesion of ethylene vinyl acetate (EVA) to solar cell solder metallization is a problem. Apparently the surface oxide condition overrides the priming treatment. Normal metal passivating treatments cannot be applied to finished solar cells.

ENGINEERING SCIENCES AREA

INTRODUCTION

The FSA Engineering Sciences Area has two primary objectives: to assist in achieving module technical feasibility by developing engineering design criteria, test methods, analysis tools, and trade-off data which support the engineering of optimum modules from a least-cost-array point-of-view, and to achieve, at an early date, technical feasibility with respect to the balance of the flat-plate array subsystem exclusive of the modules.

During the reporting period, activities within the Engineering Sciences Area emphasized array requirements generation, array subsystem development, module development, and array performance criteria and test standards development. A description of the status of each of the Engineering Sciences Area contracts was included in the 20th PIM Handout, JPL Internal Document No. 5101-205. Recent contractor and Engineering Sciences Area publications are listed on p. 41.

ARRAY REQUIREMENTS

The Array Requirements activity addresses the identification and development of detailed design requirements and test methods at the array level. Continuing areas of activity that addressed improved definition of array requirements included the establishment of module and array electrical safety criteria and the development of array-to-power-conditioner electrical interfaces (coordinated with Sandia and MIT-LL).

Safety Requirements

A necessary element of module technical feasibility, especially for residential and ILC applications, is the early development of safety requirements for incorporation at the design level. FSA Engineering Sciences Area staff members participated in the National Electrical Code (NEC) Code-Making Panel 3 (CMP-3) meeting on proposed PV revisions for the 1984 NEC in Fort Lauderdale, Florida, on January 12, 1982. The proposed new Article 690 addresses special array-related concerns (maximum allowable system voltage, specific labels or markings for modules, and module definitions) and was accepted in principle by CMP-3 voting members. After formal voting by letter ballot and processing by the NEC Correlating Committee, Article 690 will be released for public comment in June 1982.

Research aimed at developing module/panel and array subsystem electrical- and fire-safety requirements continued with an extensive reorganization of UL's draft final report to emphasize work at the module level (first phase) and to include UL's "Proposed Standard for Safety, Flat-Plate Photovoltaic Modules and Panels." This document will supersede JPL Internal Document No. 5101-164 (same title); final drafts are scheduled for publication in 1982.

ENGINEERING SCIENCES AREA

In support of array safety, General Electric Co. released a final report disclosing research on protective bypass diodes and mounting configurations for modules with power dissipation requirements in the 5-watt to 50-watt range. In addition to characterizing applicable p-on-n silicon and Schottky diodes, typical diodes were selected for representative ranges of current-carrying capacities. The study also identified heat-dissipating mounting concepts and thermal analysis defining junction temperature as a function of power dissipation.

Power-Conditioning Interface

Selection of the optimum input voltage window for power conditioning is influenced by array voltage fluctuations caused by site weather conditions. A continuing JPL in-house analytical study, using SOLMET typical-year data tapes, generated updated input for determining the optimum power-conditioning voltage, current, and power levels versus array parameters. Specific areas of activity on the array/power-conditioner task included:

- (1) Submittal of the written input supporting the analysis to Sandia Labs for their Power-Conditioning Specification and 270 review drafts to the PV community; comments on the report from the large distribution are being reviewed and collated in a JPL final report draft.
- (2) Expansion of the characterization analysis and output format to investigate the effects of using array I-V curves representing various fill factors and degraded conditions; a more complete set of results can now be provided to the JPL Lead Center and Sandia workers involved in defining the array/power-conditioner interface and in power-conditioning design efforts.
- (3) Presentation of the JPL task report and summary of recent results at the Sandia Systems PIM, February 9 to 11, in Albuquerque, New Mexico.
- (4) Conferring with MIT-LL on their array/power-conditioner investigation based on a different analysis model, which confirmed JPL's results.
- (4) Conferring with Sandia workers on their Power-Conditioning Specification, currently in the review cycle.

ARRAY SUBSYSTEM DEVELOPMENT

Array subsystem development activity focuses on the development of conceptual designs for integrated flat-plate array module support structures as a key approach to minimizing total array costs. An important output of array design is the definition of specific design requirements addressed to functional performance, interface and maintainability (at the array level).

ENGINEERING SCIENCES AREA

Integrated Residential Arrays

Residential array research continued with a review of the draft final report documenting the candidate concepts from General Electric Co. The report presents the evolution of GE's optimized integrated residential array design, displayed at the November 1981 FSA PIM. The report also documents the systems-level approach used in defining and resolving technology-performance tradeoffs and includes production and installation costs for the optimized module-array concept.

In-house efforts have focused on the utilization of PVC vinyl extrusions to complete a prototype of a direct-mounted residential-array design that obviates a 100% watertight interface between the PV module and the support structure. The array accommodates 12 frameless Block IV 2 x 4-ft modules and provides a test model to verify structural-loading, thermal-performance, environmental-endurance, assembly and module-installation considerations associated with the design. The UV-resistant PVC plastic support structure features drainage channels and has the additional advantages of being non-conductive and light in weight.

PV-Thermal Arrays

In the area of PV/thermal module development, drafts are currently under review that document the previously conducted performance and economic studies on the installation of PV/T collector systems. Included are the final task report, "Assessment of PV-T Collectors," and a manuscript titled "Viability of Unglazed PV/T Collectors for Heat-Pump Applications," accepted by the ASME organizing committee for presentation at the April 1982 conference in Albuquerque, New Mexico.

MODULE ENGINEERING

Module engineering addresses the development of design methods, analysis tools and design concepts necessary to support significant cost and performance improvements at the array-element level. Activities are conducted to clarify design tradeoffs, to develop analysis tools and test methods, and to provide general design solutions for the PV community. Specific activities included cell-reliability testing, module voltage isolation, interconnect fatigue, cell-fracture mechanics, and reliability/durability research.

Cell-Reliability Testing

The joint JPL in-house/contractor-supported R&D test program to stress-test and evaluate encapsulated cells continues in cooperation with the Environmental Isolation Task and the Cell and Module Formation Research Area. Seven new cell types from six cell manufacturers are at Clemson University for Phase 2 of the accelerated stress program. This phase will study metallization/encapsulation-system-oriented cell reliability and sensitivity. Detailed planning for this testing phase was completed; it involved development of a matrix of available cell metallization types versus a wide spectrum of recommended

ENGINEERING SCIENCES AREA

encapsulation systems. A subset of the possible matrix combinations (metallizations and encapsulation systems) was selected for initial sample experimentation. Results from the pre-test experiments verified the required level of integrity necessary for the samples and for Clemson investigations. Research and development groups at two manufacturers have also prepared a total of seven different types of encapsulated cell test specimens that will also be included in the Clemson Phase 2 investigations. Followup failure analysis from these test specimens will be coordinated closely between Clemson and the cell suppliers to understand any failure mechanisms that may be uncovered.

Module Voltage Isolation

The voltage-isolation task addresses the source and magnitude of leakage currents to ground caused by initial insulation flaws or material aging. The development effort is directed toward predictions of module life and providing for human safety. Activities during the reporting period:

- (1) The high-voltage electrical insulation environmental test chamber (HIVEC) for accelerated aging of minimodules and test coupons with experimental encapsulants was completed and is undergoing preliminary shakedown tests. Representative Block IV, PRDA and commercial designs plus test coupons, supplied by the Cell and Module Formation Research Area and the Environmental Isolation Task in a joint testing program, are scheduled for HIVEC voltage and environmental testing.
- (2) Electric insulation research activity achieved a major milestone with the final delivery of a state-of-the-art ac/dc partial-discharge pulse analyzer. The large apparatus, which has been on order from James Biddle Co. for more than a year, will serve as the key investigative tool in analyzing electrical breakdown phenomena in modules, array circuitry components and applicable insulation materials. The Cell and Module Formation Research Area is preparing coupon test specimens supporting voltage-breakdown testing of insulation systems with EVA and EMA encapsulants.
- (3) Characterization of voltage-breakdown levels of various contractor and JPL in-house polyester films and multilayer composites using the low-voltage breakdown apparatus continued with a focus on the effects of aging. A four-layer composite Mylar film was aged for two months at 40°C and 90% RH and then dried for several days in a desiccating chamber to shake down the aging equipment. The film will now be subjected to voltage breakdown testing, and changes, if any, in voltage breakdown characteristics as a result of aging will be ascertained.

Interconnect Fatigue

Examination of the mechanical-fatigue life of cell interconnects is continuing in an effort to obtain a 20-year-life-predictive model. Computer code is being generated to fit interconnect failure data to a Weibull

ENGINEERING SCIENCES AREA

probabilistic function for predicting interconnect failures. The interconnect fatigue report "Solar-Cell Interconnect Design for Terrestrial Photovoltaic Modules" was accepted by the ASME organizing committee for presentation at the April 1982 meeting in Albuquerque, New Mexico.

Fatigue testing of 5-mil-thick clad laminates and aluminum interconnects continued; the generated fatigue resistance data will be compared with the performance of commonly used silver-tinned copper interconnects. Difficulty was experienced in joining aluminum interconnects to solar cells and copper pads during earlier fatigue tests; however, the soldering problem was overcome by electroplating the aluminum strips. A second interconnect shaker was constructed to aid in fatigue testing and data-collection.

Cell-Fracture Mechanics

The fracture-mechanics study of silicon solar cells encompasses a test program to determine the effects of temperature, chemical environments and specific light intensities on the fracture strength of silicon wafers. The test program evaluates the fracture strength of silicon wafers from the same lot (same ingot and sawing condition) at several temperatures ranging from -40°C to $+150^{\circ}\text{C}$ and in several chemical environments covering the whole pH range. Several solar-cell manufacturers were asked to supply silicon wafer samples for the test program.

Efforts centered on the evaluation of the effect of light on the mechanical strength of silicon solar cells. Preliminary tests, conducted with Motorola chemical-polished Cz wafers, subjected cells to biaxial stresses in dark irradiated environments. Irradiation was provided by quartz halogen fiber-optic lamps. The results indicated significant increases in the biaxial strength of the chemical-polished Cz wafers with irradiation. Further testing is planned to identify the mechanism that causes increased strength in a lighted environment.

Reliability/Durability Research

Specific reliability and durability development efforts are addressed to provide the technical base required to achieve reliable modules with 20-year lifetimes. IITRI has completed its work in compiling reliability data on all module design technologies versus performance of each design technology in field use and in field tests.

JPL in-house efforts included the development of a humidity degradation-rate curve based on comparisons of humidity testing cycles and humidity-temperature data from SOLMET weather tapes. To obtain the required temperature-humidity acceleration factors, a contract was initiated with Wyle Laboratories to subject Blocks II, III and IV minimodules to a nine-month humidity test in environments of 40°C , 93% RH and 85°C , 85% RH. Engineering Sciences Area workers continued with the data analysis of module failures after 180 days of accelerated humidity-temperature testing. Specific visual and electrical module degradation was coordinated with Management Audit and the Module Performance and Failure Analysis Area to correlate similar module field-site degradation data and to quantify aging rates. Data from the previously

ENGINEERING SCIENCES AREA

conducted Clemson University temperature-humidity tests is under review for significant aging mechanisms and rates to supplement the Wyle test series.

Long-term temperature-soak testing with Blocks III and IV minimodules in 85°C and 100°C chambers was initiated at Wyle and supports the development of temperature-degradation rate curves. Data from these tests will be compared with the Wyle humidity-temperature test results to separate the aging effects of humidity and temperature.

PERFORMANCE CRITERIA AND TEST STANDARDS

Active interfaces are maintained between FSA Engineering Sciences Area activities and the SERI Performance Criteria/Test Standards (PC/TS) Project to establish an Interim Performance Criteria (IPC) document (Issue 2), and test standards covering both flat-plate and concentrator arrays. The Engineering Sciences Area and SERI's IPC-2 edit team focused on final reviews of environmental test methods for flat-plate modules; Arizona State University people conducted an Electrical Performance Subgroup meeting January 26, 1982, to finalize reformatted copies of electrical-performance test methods for concentrating photovoltaics.

ENGINEERING SUPPORT

Engineering interface activities provide for transfer of array requirements, specifications, conceptual designs, design guidelines, analysis tools and test methods to the overall photovoltaic community. During this reporting period JPL Engineering Sciences Area staff members participated in the Southwest Residential Experimental Station Consulting Committee meeting and the Sandia National Laboratories PV Residential Overview Committee meeting held in Las Cruces, New Mexico, December 1 and 2, 1981. The meetings provided an opportunity for industry to comment on, and influence the direction of, the federal effort in residential photovoltaics.

Several manuscripts were submitted by Engineering Sciences Area staff members for publication in IEEE Transactions on Reliability, featuring Solar Energy Devices and Systems. Topics included:

- (1) "Photovoltaic Array Power Conditioner Interface Requirements," C.C. Gonzalez.
- (2) "Advanced Residential Photovoltaic Array Designs," R.S. Sugimura, N.E. Shepard and G. Royal.
- (3) "Photovoltaic Array Grounding and Electrical Safety," A. Levins and R.S. Sugimura.
- (4) "Flat-Plate Photovoltaic Module and Array Engineering," R.G. Ross, Jr.

ENGINEERING SCIENCES AREA

Recent Contractor Publications

1. ByPass Diode Integration, Final Report No. DOE/JPL 955894-5, prepared for JPL by General Electric Co. Advanced Energy Programs, Philadelphia, Pennsylvania 19101, December 1981.
2. Integrated Residential Photovoltaic Array Development, Final Report No. DOE/JPL 955893-82/3, prepared for JPL by AIA Foundation, Washington, D.C. 20006, April 1982.
3. Integrated Residential Photovoltaic Array Development, Final Report No. DOE/JPL 955894-6, prepared for JPL by General Electric Co. Advanced Energy Programs, Philadelphia, Pennsylvania 19101, April 1982.
4. Commercial/Industrial Photovoltaic Module and Array Requirement Study, Final Report No. DOE/JPL 955698/81-1, prepared for JPL by Burt Hill Kosar Rittelmann Associates, Butler, Pennsylvania 16001, December 1981.

Recent Engineering Sciences Area Publications

1. Mon, G.R., Moore, D.M., and Ross, R.G., Jr., Interconnect Fatigue Design for Terrestrial Photovoltaic Modules, JPL Document No. 5101-173, Jet Propulsion Laboratory, Pasadena, California, March 1, 1982.

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

INTRODUCTION

The overall objective of the Module Performance and Failure Analysis (MPFA) Area is to evaluate the reliability and durability of modules that are constructed using the improved techniques researched in the other FSA Tasks and Areas. This is accomplished through a structured program of:

- (1) Procurement of modules to a specification.
- (2) Environmental stress testing.
- (3) Detailed failure analysis.
- (4) Operation in a field environment to obtain data that will:
 - (a) Confirm the reliability and durability of the tested article.
 - (b) Confirm the validity of the environmental test regimen imposed in item (2).

Accomplishment of this work also requires implementation of an accurate repeatable and reliable performance measuring system. Work activities and accomplishments in all of these activities of the Area during the reporting period are described below.

MODULE DEVELOPMENT

Block IV Design and Qualification

Work came to an end on one of the two remaining open contracts for Block IV module designs. The ARCO Solar, Inc., residential module failed to pass the environmental qualification test, and ARCO declined to make further changes in the design essential to passing the tests. Delamination of the Tedlar front cover in the area of the bends in the steel substrate of the batten seam module was the most obvious defect. The Photowatt International, Inc., module passed all environmental tests, but failed the final high-pot test. The substitution of a continuous rather than pieced vinyl gasket around the periphery of the laminate is expected to solve this problem.

Block IV Production Orders

Work on production orders has not flowed smoothly. ARCO did deliver the full complement of intermediate-load modules within two months of the release, but Applied Solar Energy Corp. modules delivered under the purchase order developed delamination in the encapsulation system. This problem has been studied and found to be the result of improper assembly. A sample of new modules has been received and are presently in the thermal test cycle. If these modules are satisfactory, the remainder of the production order will be delivered.

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

The requisition for the purchase of ARCO residential modules was cancelled because these modules did not survive the environmental tests and ARCO declined to continue work. The Photowatt purchase order remains on hold pending completion of the design contract.

Solarex Corp. modules repaired to a specified procedure have been tested at JPL and the repair procedure has been found to be satisfactory. Solarex will now be able to deliver the modules remaining on these orders.

Block V Design

Design studies of modules for Block V were carried through the preliminary design phase by six contractors: ARCO, General Electric Co. Mobil Tyco Solar Energy Corp., RCA Corp., Solarex, and Spire Corp. These generally were studies resulting in a paper design only; however, the GE module was fabricated and tested as one of the candidate modules for the Georgetown Project, and ARCO assembled a laboratory model of its proposed design. Many of the features of the designs are summarized in the illustrative material found in this report in the presentation made by L. D. Runkle during the plenary session of the 20th PIM (see p. 99). Briefly, a few of the trends are:

- (1) Module power output is increasing.
- (2) Efficiencies of modules appear to be leveling off around a maximum of 11.5% measured at the peak power conditions
- (3) All designers chose to encapsulate modules with EVA.
- (4) All modules use a low-iron glass as the top surface.
- (5) Redundant interconnects are in universal use.
- (6) Diode protection is applied around series blocks of 12 cells as a maximum.
- (7) Ribbon cells have made their appearance in a JPL Block module design.
- (8) The accepted configuration appears to have shifted to modules without metallic frames.

MODULE TEST AND EVALUATION

Performance Measurements

The selection, fabrication and calibration of 15 new reference cells have been completed in support of Sandia Laboratories and for other module testing by JPL. Spectral response and identification of these cells are also complete. Temperature coefficient measurements and final sealing cells are awaiting the completion of modifications to the large-area pulsed solar

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

simulator (LAPSS) II hardware. In addition, four new cells will be selected, fabricated and calibrated for use in evaluating Mobil Tyco modules.

A proposal to build and calibrate reference cells has been received from DSET Laboratories, Inc. This proposal is presently in the negotiation state. Pending successful negotiations, JPL plans to provide DSET with three types of cells: Spire, ASEC (3SR), and Mobil Tyco (production); DSET will provide four calibrated cells of each type to JPL for evaluation.

During the past few months, experiments were conducted to evaluate a Schott GG-4 filter for use with the LAPSS systems to simulate AM1.5 spectral irradiance. A paper on the results was presented at the 20th PIM. The filter reduces the intense ultraviolet output of the LAPSS, producing a light source that closely approximates a terrestrial AM1.5 spectrum. A group of four calibrated reference cells were intercompared and peak errors of as much as 7% for the unfiltered LAPSS were reduced to 1% for the LAPSS with the Schott GG-4 filter. The tests also revealed that using the red-blue ratio as a method of selecting reference cells can produce errors as high as 6%. It is apparent that with this filtered LAPSS it will not be necessary to use spectrally matched reference cells to measure the output of any existing modules and it should also provide an excellent means of providing secondary calibrated reference cells of high accuracy. Further tests are planned to determine the filter stability and possible limitations on its use.

Equipment failures in the LAPSS system forced only a few short-term shutdowns of the PDP 11/60 computer, which is now backed up by an operational Nova minicomputer in the LAPSS I. Simultaneous operation of the LAPSS I and LAPSS II with the PDP 11/60 computer has not been totally achieved; however, software modifications are in progress that will allow simultaneous operation except when one of the LAPSS systems is actually being flashed and the acquired data is being transmitted to the PDP 11/60. Real-time messages will be displayed on the other LAPSS console when a flash is in progress. The LAPSS II is presently being checked and modified for compatibility with the high-current 50-A load.

Electrical performance testing using the two simulators has been in great demand. In addition to the measurements required during the testing of the Georgetown modules and the regular testing sequences, minimodules from the Engineering Sciences Area and the Environmental Isolation Task have required measurements in connection with the accelerated environment testing program and the reliability and durability studies on encapsulants. On top of that, the field-test task has had modules measured before installation in the field.

Environmental Testing

Testing six sets of modules to the requirements of the Block V specifications for the Georgetown project has been the principal activity in the environmental facility. The modules were received at JPL in mid-January and the tests flowed generally according to the forecast schedule. Most testing was completed by the end of the reporting date; however, the sheer bulk of one specimen, which represented a roof section, delayed completion of that particular set of modules. Results of this testing have been communicated

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

to Oak Ridge Operations and Georgetown University people, who also took a first-hand look at the test results as participants in the PIM.

During the course of the testing program for Georgetown modules, tests on the JPL Block IV or commercially produced modules were run when feasible. The results of these later tests are given in Table 3. As can be seen from the table, testing has been performed on Block IV and commercial modules at some of the Block V levels. Several modules have performed satisfactorily in some of the Block V tests, but no modules other than the Georgetown modules have been subjected to the full schedule of Block V tests.

Field Test

Field Test activities were centered on the restructuring plan. The main effort consisted of installing the modules required to form arrays, installing and activating the irradiance-measuring instruments and completion of the portable I-V array data logger.

Three of the arrays were installed at the JPL test site. The installation included mounting the modules, wiring them into array configurations, linking them to the computer, and connecting the arrays to fixed loads. Each array is made up of modules from the same manufacturer. The Motorola Inc. array contains 20 Block IV intermediate-load modules, the ARCO array contains 18 automated assembly-line modules, and the Solarex array has 22 Block IV intermediate-load modules. The fixed loads approximate the maximum power point for each array. Because of computer problems, daily data on these modules and arrays is not being obtained but is expected soon.

In addition to the arrays, four modules from different manufacturers were installed and instrumented with thermocouples to monitor the temperature of the cells in the module under open-circuit conditions. The modules were manufactured by Motorola, ARCO, ASEC and Solarex. Each module has three thermocouples mounted on the substrate behind cells at the top, middle and bottom. The Motorola and ARCO modules have three additional thermocouples mounted on the substrate next to the cells that have thermocouples. When daily data acquisition is initiated their data will be acquired along with the module I-V data.

The instruments used to measure irradiance at the JPL test site were installed and operated for several weeks. The installation and a preliminary analysis of some of the data were presented at the 20th PIM. The analysis included the effects of turbidity, time of day, and mounting plane on the diffuse-to-total-irradiance ratios.

The portable I-V high power array data logger was displayed at the 20th PIM. A power supply was used to simulate an array so that the process of obtaining, displaying and storing an I-V curve could be demonstrated. The software required to utilize fully the logger's capabilities is 75% complete. When the software is completed the system must be checked out using arrays with high voltage and current output.

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

Table 3. Test Results for Block IV Modules

Vendor Code	No. of Modules Tested	Construction (From Top Down)	Test Spec	Tests Completed	Results
G/Prod	1	Glass, adhesive, RTV, weatherproof paper	V	Hot-spot	Cell electrical degradation 16%, 9% and 4%; module degradation 3%
G/Prod	2	Glass, adhesive, RTV, weatherproof paper	IV	T~, H~	Air bubbles
S/Prod W/Repairs	2	Glass, EVA, ripstop, Mylar/ alum; aluminum frame	IV	T~, H~	Diode in J-box separated from leads
S/Prod	2/1	Glass, EVA, ripstop, Mylar/ alum; aluminum frame	V	T~, HF T-200~	Minor ground wire corrosion; some grids faded; electrical OK
UR/Proto	4	Tedlar, EVA, galv steel pan; mounted on JPL wood frame	IV	T~	Tedlar/encap top surface shrinkage and delamination; elect degrad 1 module; design to be discontinued
V/Proto	5	Glass, PVB, Tedlar/alum/ Tedlar; aluminum frame	IV	All	Hi-pot failure post-test, 2 modules; intermittent open in module in MI
Y/Prod W/Repairs	2	Glass, EVA, Crane glass, EVA, Tedlar; aluminum frame	IV	T~ HF	Cracked cells, some touching, air bubbles; wrong test run; edge sealant split, air bubbles
Test Code:		T~ = 50 temperature cycles H~ = Blk IV humidity test HF = 850/85% humidity-freeze HS = Hot-spot test MI = Mechanical integrity			
		Prod = Production module Proto = Blk IV prototype			

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

Table 3. Test Results for Block IV Modules (Cont'd)

Vendor Code	No. of Modules Tested	Construction (From Top Down)	Test Spec	Tests Completed	Results
A	6/1	Clear acrylic, encap, white acrylic	V	T~ HS	6 elec failures; cracked ICs air bubbles, discoloration
Q2	6/1	Glass, encap, Tedlar; aluminum frame	V	T~, HF, MI	Air bubbles, delam at frame seal 1 cell crack
R	6/1	Glass, encap, Tedlar; aluminum frame	V	HS T~, HF	Tedlar wrinkled Plastic cracked at J-box cover insets, 2 modules
				HS	Tedlar wrinkled, minor discoloration
Test Code: T~ = 50 temperature cycles HS = Hot-spot test HF = 85°/85% humidity-freeze MI = Mechanical integrity					

MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

FAILURE ANALYSIS

The quarterly Problem/Failure Report (PFR) summary issued in February showed a total of 1108 PFRs issued since the inception of FSA. Of these, 978 have been investigated and formally closed. PFRs are written when anomalous performance occurs, whether during qualification testing, operation in the field, or special tests, or on other occasions such as incoming inspection. Most (617) of the PFRs were written during qualification testing, which is regarded as part of the design sequence for a solar cell module. It is notable that more than half of those written during the qualification testing sequence are issued after the thermal cycling tests.

Copies of the new and the closed-out PFRs were sent to the involved manufacturers in November 1981 and again in February 1982.

A special effort was made to study the effects of temperature on the level of leakage current for a particular module. JPL specifications require that a voltage-isolation or hi-pot test be run at room temperature to assure that the electrically active portion of a solar cell module is sufficiently isolated from the module frame or whatever conducting mounting is used. Typically, as in Block IV intermediate-load modules, a potential of 2000 V is applied between the cell string and the frame of the module. The current flow is to be less than 50 μ A. For the particular laminated module studied, which used a PVB encapsulant and a back skin with a metal foil in a Tedlar sandwich, it was found that leakage current was strongly dependent upon temperature. At nominal operating temperatures between 40° and 60°C, leakage currents in excess of 50 μ A for test voltages down to 500 Vdc are expected. These experiments were described briefly at the 20th PIM by A. Shumka (see p. 500).

The laser-scan facility has been modified to accept modules assembled up to 4 x 6 ft. Laser scanning is now used routinely to screen modules for latent defects before running through the environmental test sequence. The large influx of modules for Georgetown testing constituted a large part of the laser-scanning effort.

PROCEEDINGS

INTRODUCTION

The 20th Project Integration Meeting of the Flat-Plate Solar Array Project (FSA) of the Jet Propulsion Laboratory (JPL) was held at the Pasadena Center, Pasadena, California, on April 21 and 22, 1982. The meeting had two themes: Future Photovoltaic Research Needs, and FSA Progress.

In plenary session presentations were offered on the redirection of the Project, on needs in photovoltaic research, and on the status of several research areas and PV projects.

A summary of plenary session presentations follows:

M. Prince, chief of the Collector Research and Development Branch of the U.S. Department of Energy, presented DOE budget plans for 1982, including general funding levels and key program achievements, and summarized activities that are cost-shared with industry; cell efficiency improvements with time, and industry accomplishments.

Eugene Frankel, Science Consultant to the Subcommittee on Energy Development and Applications, U.S. House of Representatives, discussed attitudes in the U.S. House of Representatives regarding prospects for future funding of solar energy activities. In seeking adequate funding for photovoltaics, the photovoltaic industry must offer Congress a unified position and not, as it has in the past, a fragmented set of inconsistent positions, he said; Congress has heard in the past a number of voices, some saying that emphasis should be on advanced R&D, some that technology development is more important, others calling for emphasis in still other areas. He said that Congress is listening to industry, and is waiting for instructions from the photovoltaics community, but they must be clear and simple, basic statements of principle, rather than pleas for a clutter of projects and studies that do not represent the needs of photovoltaics as a whole.

W. T. Callaghan, Flat-Plate Solar Array Project (FSA) Project Manager, presented the latest thinking about how FSA will redirect its activities away from its recent product-oriented technology development efforts and toward longer-term research on technical problems that could limit future large-scale use of photovoltaics. With the emphasis on research, the Project is now organizing a series of workshops addressing the key basic technological questions by specific topic. Intervals between Project Integration Meetings are being extended because there are fewer contracts within FSA and because work under those contracts has been attenuated.

M. H. Leipold of JPL summarized the status of polysilicon activities, highlighted by Union Carbide Corp. (UCC) moving the silane portion of the experimental process system development unit (EPSDU) to Washougal, Washington. UCC is paying for the completion and operation of the silane EPSDU, and will provide its test data in return for title to the equipment. DOE will continue

PLENARY SESSION: SUMMARY

to fund research on the silane-to-silicon deposition process. Progress also continues on the Hemlock Semiconductor Corp. dichlorosilane process.

A summary of advanced Cz ingot-growth activities was presented by R. L. Lane of Kayex Corp. Kayex has grown five ingots (totalling 150 kg) from one crucible by use of chunk silicon replenishment between ingot pulls. The cost of the ingot growth has been reduced from \$80/kg (conventional Cz growth) to \$20/kg. Further improvements can be made by achieving a better understanding of crystalline silicon growth and the influence on growth of contaminants from the atmosphere and/or the crucible. This should lead to a higher percentage of monocrystalline growth and possible increased growth rates.

The FSA Block V Module design efforts of six manufacturers were summarized by L.D. Runkle of JPL. General Electric Co., Mobil Tyco Solar Energy Corp. and Spire Corp. made residential designs and ARCO Solar, Inc., RCA Corp. and Solarex Corp. made module designs for intermediate-load applications. This was Mobil Tyco's and RCA's first participation in FSA Block module efforts. It is planned that a few prototype modules of each design will be fabricated. The modules incorporated advanced concepts, were larger than earlier ones and had high power output.

G. J. Jones of Sandia National Laboratories summarized the results of a number of photovoltaic central power-station studies. Analysis based upon vendor quotes and construction contractor bids indicate that \$50/m² for area-related costs for flat-plate arrays is achievable. A study of electrical design tradeoffs for multimegawatt systems was recently completed by Bechtel Group, Inc. The values of photovoltaic central-station plants for various regions can be determined from an energy scenario effects study completed by GE.

S. L. Leonard (Aerospace Corp.) discussed the potential value to an organization of third-party financing, facilitated by federal and state tax incentives.

D. Price of Georgetown University and Dr. Yudi Gupta of Science Applications, Inc. (SAI), described Georgetown University plans for a 300-kW roof-mounted photovoltaic power system for GU's new intercultural center, as a part of a new energy-efficient power system at the University.

R. V. Powell of JPL presented a status report on plans for the Sacramento Municipal Utility District (SMUD) 1-MW photovoltaic power plant. DOE, the California Energy Commission, and SMUD will fund the project cooperatively. Negotiations are proceeding to complete arrangements among the three parties.

A. T. White of ARCO Solar presented an overview of the new 1-MW photovoltaic central-station installation that ARCO Solar will install in 1982. The power generated at this site, in the desert northeast of Los Angeles, will be purchased by Southern California Edison Co. Approximately 10 kW of flat-plate modules will be mounted on each two-axis tracking unit.

M. Sagenkahn of Shell Oil Co. presented a summary of economic forecasts of U.S. energy supply and consumption. Consumption by user groups and supply by various technologies, including projected growth rates, were shown. He forecast future syncrude and syngas capabilities as well as future renewables.

PLENARY SESSION: SUMMARY

As fuel prices increase the rate of energy consumption decreases faster than was expected 12 to 18 months ago. Consequently, future fuel price estimates have been revised downward. He noted that renewables must stand on their own merit if they are to be widely used. Eventual economic competitiveness of photovoltaics is more a function of manufacturing costs per peak watt than of price increases of traditional power. The biggest uncertainty in energy forecasts is the possibility of petroleum supply disruptions, which necessitates development of alternative energy sources.

E. L. Ralph of Spectrolab, Inc., presented a history of terrestrial PV showing that photovoltaic potential was well perceived and a good technology development plan was formulated and implemented. Progress has been made but there is a need to formulate an updated plan based upon today's situation.

R. W. Taylor of the Electric Power Research Institute described the parameters used by an electric utility in performing tradeoff analyses of potential alternative energy sources. The analyses vary with many factors, including utility location, type of consumer loads, local fuel availability and costs. Examples were shown for a number of utilities. Many technical, institutional, and operational factors also must be considered. Examples of photovoltaic cost-versus-efficiency tradeoff charts relating module and balance-of-system costs against efficiency were shown for flat-plate and concentrator systems.

E. Kern of the Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) discussed research on residential PV power systems based upon the experience of MIT-LL in implementing the DOE Residential Demonstration Project, especially the Northeast Residential Experiment Station (NE RES). There is an immediate need for improved power-conditioner operational and reliability capabilities. Continuing evaluation of photovoltaic power systems is required to verify long-term performance, reliability and utility interface effects. In the long term, the price of photovoltaic power systems must decrease, especially of modules.

R. Little of Spire Corp., as the president of a small independent photovoltaic manufacturing company, has a view of the future of photovoltaics different from that of a large, well financed company such as an oil-company-supported PV business. It is difficult for small companies to continue in business today without government support of research and development because the potential revenue from research and development is still small compared with investment requirements. Historically, most technical innovation has come from small independent businesses; thus, advancements in photovoltaic technology can be expected to slow down until there is a healthy climate for small business.

An industries perspective of PV research needs was presented by Juris Kalejs for R.V. Ravi of Mobil Tyco Solar Energy Corp. Objectives and features of industry needs were discussed for the materials, devices, processes, and reliability research categories.

S. Ovshinsky of Energy Conversion Devices, Inc. (ECDI), presented a perspective of the background and progress made by ECDI in amorphous silicon solar cells. Progress in the last year or two has shown that amorphous silicon cells have potential as a competitive energy source. ECDI has a joint business venture with Standard Oil Co. (Ohio) to continue the investigation of this photovoltaic technology.

PLENARY SESSION: SUMMARY

M. Wolf of the University of Pennsylvania described the historical progression of efficiency improvements, cost reductions, and performance improvements in modules and photovoltaic systems. The potential for future improvements in photovoltaic device efficiencies and cost reductions continues as device concepts, designs, processes, and automated production capabilities mature. Additional step-function improvements can be made as today's simpler devices are replaced by more sophisticated devices.

T. Surek of the Solar Energy Research Institute (SERI) presented a summary of an evaluation of advanced research and development topics in photovoltaics that was conducted by SERI. The intent was to develop priorities in a list of advanced research and development activities. Thirty-five activities in 10 major categories were evaluated by their contributions to basic scientific advances, potential impact on further technology development by private industry, and priorities for federal advanced research and development funding.

The following pages present plenary session discussions, followed by those delivered in the parallel technology sessions.

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Plenary Session

NATIONAL PHOTOVOLTAICS PROGRAM

U.S. DEPARTMENT OF ENERGY

✓ M. Prince

Program Structure

Stage of Development PY Program Category	Basic and Applied Research	Exploratory Development	Technology Development	Engineering Development	Demonstration	Commercial Production and Operation
Material, Cell, Device R&D		LTF ↓	TF ↓			
High-Risk Collector R&D		\$0.70/W _p ↓	TF ↓			
High-Risk Sub-System R&D		\$0.40/W _p ↓	TF ↓			
High-Risk System R&D						

PRIVATE INDUSTRY ACTIVITIES

FY82 Funding Levels by Program Element

(MILLIONS OF DOLLARS)

<u>PROGRAM ELEMENTS</u>	<u>FY 82 APPROPRIATIONS</u>
MATERIALS RESEARCH	23.9
ADVANCED CONCEPTS	11.6
SUPPORTING RESEARCH	2.2
SYSTEMS RESEARCH	20.5*
TECHNOLOGY DEVELOPMENT	3.6
EXPERIMENTS	12.2**
CAPITAL EQUIPMENT	<u>4.0</u>
TOTAL	78.0

* INCLUDES THE SE RESIDENTIAL EXPERIMENTAL STATION

** INCLUDES COMPLETION OF NATIONAL EXEMPLAR PROJECT AND THE 1 MW SHUD PROJECT

PLENARY SESSION: M. PRINCE

Detailed Funding Levels With Organizational Responsibility

<u>ACTIVITY</u>	<u>RESPONSIBLE AGENCY</u>	<u>FUNDING (\$ MILLIONS)</u>
<u>MATERIALS RESEARCH</u>		
AMORPHOUS MATERIALS*	SERI	3.8
STABILITY & EFFICIENCY OF THIN FILMS	SERI	4.1
HIGH EFFICIENCY DEVICE CONCEPTS	SERI	3.3
SILICON AND POLYCRYSTALLINE SHEET*	SERI	2.5
SILICON MATERIAL PURIFICATION*	JPL	2.9
RIBBON AND SHEET SILICON RESEARCH	JPL	6.8
ENVIRONMENTAL DEGRADATION RESEARCH	JPL	1.5
<u>ADVANCED CONCEPTS</u>		
ELECTROCHEMICAL MATERIALS AND CELLS*	SERI	2.0
CONCENTRATOR MATERIALS AND CELLS	SANDIA	2.2
POWER QUALITY AND CONTROL RESEARCH*	SANDIA	3.1
CELL AND MODULE FORMATION RESEARCH	JPL	4.7
<u>SUPPORTING RESEARCH</u>		
DIAGNOSTIC EQUIPMENT	SERI	2.2
<u>SYSTEMS RESEARCH</u>		
SYSTEMS RESEARCH	SANDIA	1.1
CRITICAL SUBSYSTEMS DEVELOPMENT	SANDIA	1.3
CONCENTRATOR RESEARCH AND TESTING	SANDIA	4.9
DATA COLLECTION OF EXPERIMENTS AND ANALYSIS	SANDIA	4.8
SYSTEMS EXPERIMENTS, OPERATIONS/ CLOSEOUT	VARIOUS	5.6
ENGINEERING SCIENCES RESEARCH	JPL	3.4
SE RES	SANDIA	2.0
<u>TECHNICAL DEVELOPMENT</u>		
SILICON TECHNOLOGY DEVELOPMENT	JPL	3.6
<u>OTHER</u>		
SMUD*	HQ	6.8
NATIONAL EXEMPLAR	ORO	5.4
	TOTAL	78.0

Program Cost Sharing With Industry

<u>ACTIVITIES</u>	<u>DOE SHARE*</u>	<u>PRIVATE SHARE</u>
AMORPHOUS MATERIALS	\$.8 M	\$.2 M
SILICON AND POLYCRYSTALLINE SHEET	.6 M	.2 M
ELECTROCHEMICAL MATERIALS & CELLS	2.5 M	.7 M
SILICON MATERIAL PURIFICATION	1.5 M	8.5 M
CELL AND MODULE FORMATION RESEARCH	4.0 M	.9 M
SNWD PROJECT	6.8 M	5.2 M

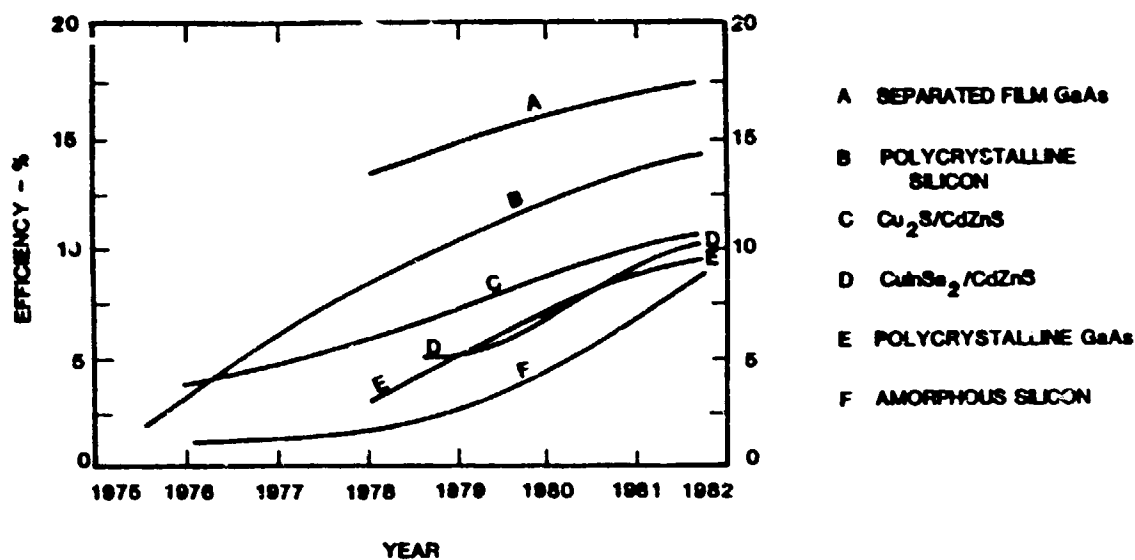
* APPLIES TO COST-SHARED CONTRACTS ONLY

Major Accomplishments

<u>TECHNOLOGY ELEMENTS</u>	<u>1975</u>	<u>1981</u>
o EFFICIENCY		
- SILICON	8%	20%
- THIN FILMS	1-3%	5-11%
o CELL COSTS	\$50/Wp	\$7/Wp
o MODULE LIFE (TERRESTRIAL)	1-2 YEARS	10 YEARS
o TERRESTRIAL SYSTEM EXPERIMENTS	Few small remote uses	2,700 small experiments (FPUP); 15 major projects (as large as 350 kWp)
o INDUSTRIAL BASE	A few small specialty companies (several kWp sales in 1975)	Rapidly expanding industrial base; more than 15 cell suppliers (5 MWp sales in 1981)
o FABRICATION TECHNOLOGY	Expensive manual operation	Semi-automated pilot production of cells; ribbon processes near commercialization

Cell Efficiency vs Time for Non-Single-Crystal Silicon Devices

(THIN FILM TECHNOLOGIES)



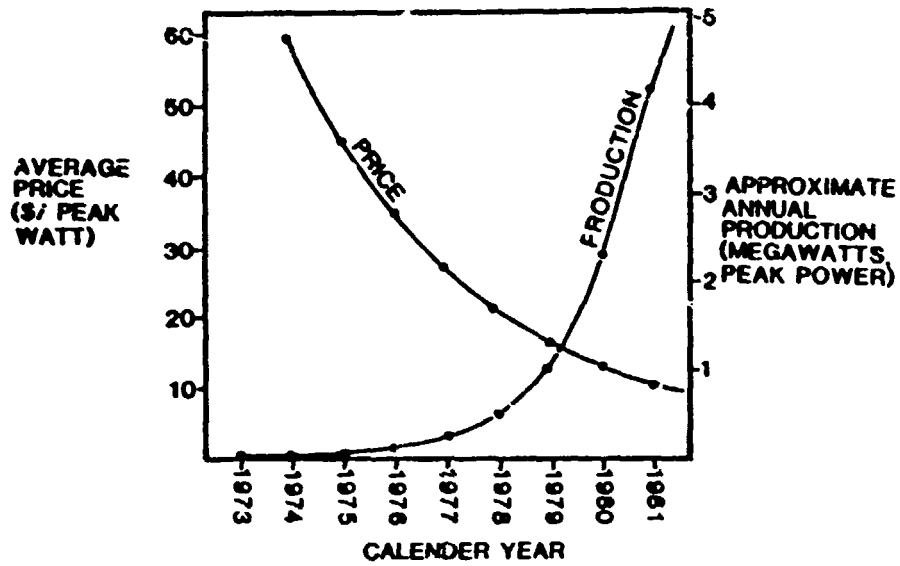
State of U.S. PV Industry

- (1) DEVELOPED HIGHLY-RELIABLE PRODUCTS TO SUPPLY REMOTE ELECTRICITY FOR COMMUNICATIONS, CORROSION CONTROL, NAVIGATIONAL AIDS, HOME AND FARM USES
- (2) INVESTED IN INFRASTRUCTURE TO DELIVER AND SERVICE THESE PRODUCTS
- (3) INCREASED SALES AND REVENUES AT A VERY HEALTHY RATE

	1979	1980	1981	1982 (EST)
SALES	1.4 MWp	3.2 MWp	5 MWp	7.5 MWp
REVENUE	\$30 MILLION	\$50 MILLION	\$75 MILLION	\$100 MILLION

- (4) INVESTED APPROXIMATELY \$40 MILLION IN 1981 INTO RESEARCH ON IMPROVED PHOTOVOLTAIC CELLS AND MODULES

History of U.S. Prices and PV Module Production



Dr. J.

FSA's FUTURE ROLE

JET PROPULSION LABORATORY

W.T. Callaghan ✓

Future Role

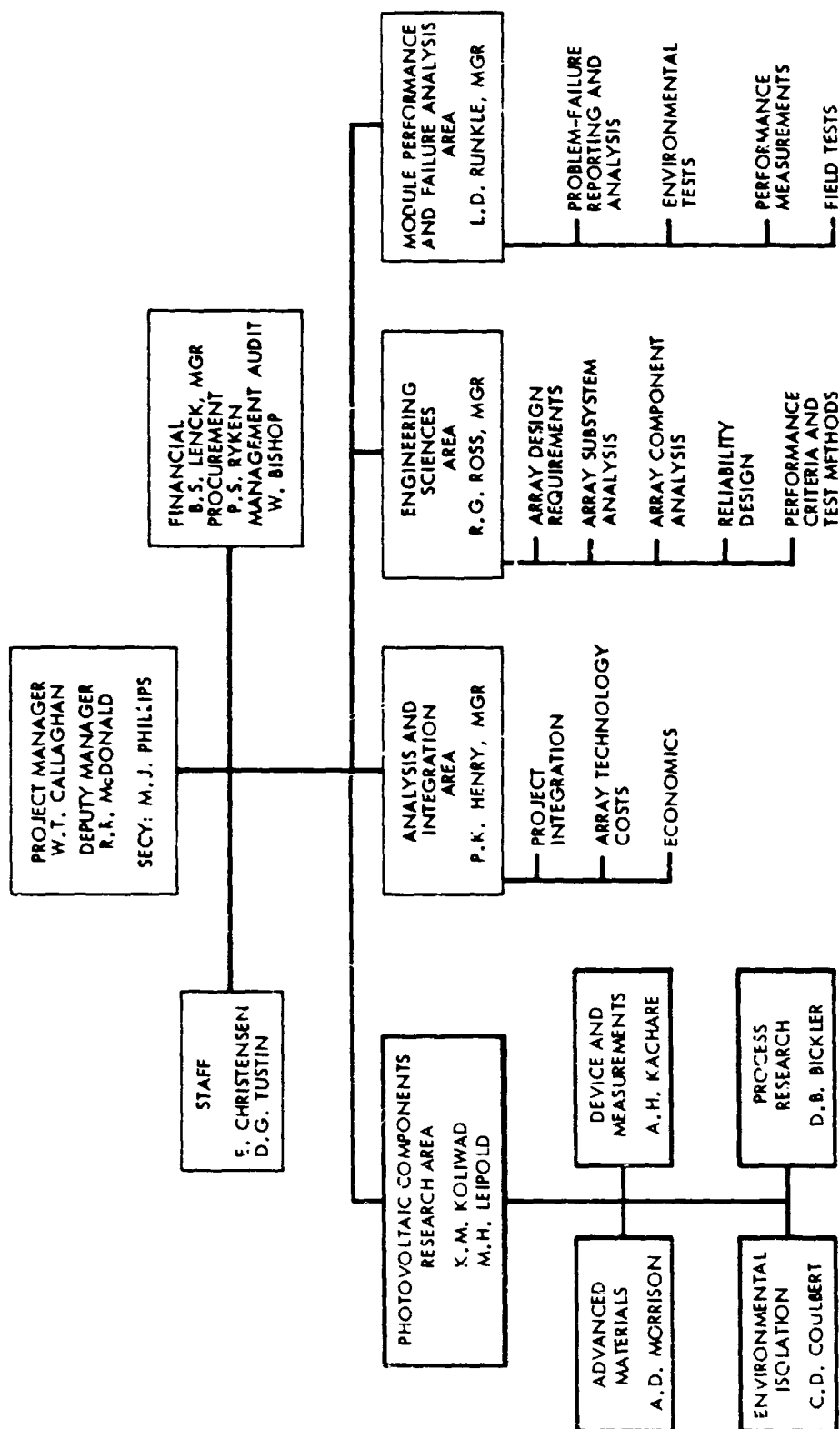
• OBJECTIVES

- TO PURSUE ADVANCED CRYSTALLINE SILICON PV TECHNOLOGIES FOR POTENTIAL USE LATE IN THE 1980s AND IN THE 1990s
- TO CONTINUE SPONSORSHIP OF RESEARCH AND TECHNOLOGY EVOLUTION ON ADVANCED THICK-MATERIAL FLAT-PLATE PHOTOVOLTAIC MODULES AND ARRAYS
- TO COMMENCE THE ACTIVITIES REQUIRED TO MOVE THIN-FILM TECHNOLOGIES INTO MODULE DEVELOPMENT
- TO CONTINUE TO STIMULATE TRANSFER OF KNOWLEDGE THROUGHOUT THE PHOTOVOLTAIC COMMUNITY

Project Plans

- TO SPONSOR TECHNOLOGY ACTIVITIES THAT HAVE THE POTENTIAL FOR MAKING MODULES/ARRAYS VIABLE FOR LARGE-SCALE APPLICATIONS, SUCH AS CENTRAL STATIONS AND ROOF-TOPS
- TO STRIVE FOR HIGH EFFICIENCY COUPLED WITH SIGNIFICANT COST REDUCTION FOR LOWEST POWER GENERATION COSTS
- TO REDUCE TECHNICAL BARRIERS TO HIGH-PERFORMANCE, LONG-LIFE, RELIABLE MODULES AND ARRAYS
- TO CONTINUE TO FUND UNIVERSITIES, INDUSTRY, AND OTHER ORGANIZATIONS FOR PERFORMANCE OF MOST OF THE WORK
- TO CONTINUE ECONOMIC ANALYSIS TECHNIQUES FOR COMPARISON OF ALTERNATIVE RESEARCH OPTIONS

FLAT-PLATE SOLAR ARRAY PROJECT



New Task Objectives

TO EXTEND OUR KNOWLEDGE AND CAPABILITIES TO USE THE FOLLOWING TECHNOLOGIES FOR PHOTOVOLTAIC COMPONENTS:

- **ADVANCED MATERIALS (A.D. MORRISON)**
SILICON AND NON-SILICON MATERIAL SYNTHESIS,
PREPARATION AND SHEET GROWTH FOR PHOTOVOLTAIC
DEVICES
- **DEVICE AND MEASUREMENTS (A.H. KACHARE)**
DEVICE STRUCTURE, MATERIAL-DEVICE PROPERTY
INTERACTION, SILICON AND NON-SILICON DEVICE
PHYSICS, MEASUREMENT TECHNIQUES FOR PHYSICAL,
CHEMICAL AND ELECTRICAL EVALUATION, AND
MATERIAL CHARACTERIZATION
- **ENVIRONMENTAL ISOLATION (C.D. COULBERT)**
ENCAPSULATION MATERIAL FORMULATION, PROPERTIES,
LIFE-LIMITING DEGRADATION MECHANISMS, MODULE
DURABILITY, PERFORMANCE PREDICTABILITY,
ASSESSMENT METHODOLOGIES AND ADVANCED
PACKAGING CONCEPTS FOR SILICON AND NON-SILICON
DEVICES
- **PROCESS RESEARCH (D.B. BICKLER)**
RESEARCH IN SILICON AND NON-SILICON PROCESS
ELEMENTS SUCH AS SURFACE PREPARATION, JUNCTION
FORMATION, METALLIZATION, ANTI-REFLECTION
COATING, AND SYNERGISTIC EFFECTS OF THESE STEPS
ON CELL AND MODULE FABRICATION

Objectives and Plans

SILICON MATERIAL

OBJECTIVE
SPONSOR THEORETICAL AND EXPERIMENTAL RESEARCH ON SILICON MATERIAL REFINEMENT TECHNOLOGY SUITABLE FOR FLAT PLATE SOLAR ARRAYS

PLANS

- CONDUCT RESEARCH IN NEW REACTOR CONCEPTS THAT ENABLE SHORTER CYCLES FOR SILICON DEPOSITION RATES USING CHLOROSILANE AND SILANE PRECURSORS
- CONDUCT RESEARCH IN NEW CONCEPTS FOR FLUORIZED BED REACTOR TECHNOLOGY FOR CHLOROSILANE OR SILANE CHEMICAL SYSTEMS
- COMPLETE ONGOING EFFORTS TO RESOLVE THE KEY CRITICAL TECHNICAL ISSUES IN THE TRANSITION FROM THE SILANE TO SILICON AND THE DICHLORSILANE TO SILICON PROCESSES

SILICON SHEET

OBJECTIVE
CONDUCT RESEARCH ON THE CRITICAL ELEMENTS OF SILICON SHEET GROWTH TO ACHIEVE THE TARGETS OF A SILICON SHEET TECHNOLOGY COMPATIBLE WITH FUTURE SOLAR CELL REQUIREMENTS

PLANS

- PERFORM RESEARCH ON THE LIMITS TO CRYSTALLIZATION RATES IN SILICON GROWTH
- PERFORM THEORETICAL AND EXPERIMENTAL RESEARCH ON THERMAL STRESSES GENERATED IN THE GROWTH OF WIDE AND THIN SILICON RIBBONS
- PERFORM RESEARCH TO FURTHER UNDERSTANDING OF THE INFLUENCE OF GROWTH AMBIENT ATMOSPHERE CHEMISTRY ON THE CRYSTALLIZATION PROCESSES AND SILICON MATERIAL QUALITY
- CONTINUE RESEARCH ON THE BASIC MECHANISMS OF CUTTING SILICON AND THE INTERACTION OF SILICON SURFACES WITH EXPERIMENTAL PARAMETERS
- CONTINUE CHARACTERIZATION OF SILICON SHEET MATERIAL WITH INNOVATIVE TECHNIQUES

CELL AND MODULE FORMATION

OBJECTIVE
SPONSOR RESEARCH ON ADVANCED CELL AND MODULE FORMATION TECHNIQUES

PLANS

- CONDUCT RESEARCH IN THE FORMATION AND CHARACTERIZATION OF ELECTRICALLY CONDUCTIVE BILAYES
- CONDUCT RESEARCH ON THE INFLUENCE OF POLYCRYSTALLINE GRAIN BOUNDARIES UPON JUNCTION FORMATION AND METALLIZATION
- PERFORM RESEARCH ON THE PHYSICS OF SURFACE FIELD FORMATION
- PERFORM RESEARCH ON THE PHYSICS OF CORROSION REACTIONS AT METALLIC INTERFACES
- CONTINUE RESEARCH ON NON MASS ANALYZED ION IMPLANTATION TECHNIQUES FOR JUNCTION FORMATION AND METALLIZATION SYSTEMS AND MODULE ASSEMBLY TECHNIQUES

ENVIRONMENTAL ISOLATION

OBJECTIVE
SPONSOR RESEARCH ON AGING DEGRADATION CHARACTERISTICS AND THEIR INFLUENCE UPON MODULE DURABILITY AND RELIABILITY

PLANS

- CONDUCT RESEARCH IN LONG TERM PHOTO THERMAL DEGRADATION MECHANISMS IN POLYIMIDES ESTABLISH MODIFIED AND VALIDATE INVESTIGATE ENCLOSURE INTERFACIAL STABILITY CRITERIA AS AFFECTED BY BONDING TECHNIQUES, DISSIMILAR MATERIALS AND OPERATIONAL ENVIRONMENTS
- CONDUCT RESEARCH IN CORROSION MECHANISMS IN MODULE INTERNAL CIRCUIT ELEMENTS VERIFY DEGRADATION RATES AND CONTROL CRITERIA
- INVESTIGATE OPERATING TEMPERATURE LIMITATIONS IMPOSED BY MODULE DESIGN AND MOUNTING AND HOT SPOT SENSITIVITY
- INVESTIGATE AND APPLY ACCELERATED AND DURABILITY TESTING TECHNIQUES AND LIFE PREDICTION METHODS

ENGINEERING SCIENCES

OBJECTIVE
SPONSOR RESEARCH ON ADVANCED MODULE AND ARRAY ENGINEERING SCIENCE ACTIVITIES THAT WILL LEAD TO HIGH PERFORMANCE, SAFE, RELIABLE LONG LIFE DESIGNS

PLANS

- CONTINUE THEORETICAL AND EXPERIMENTAL RESEARCH TO CHARACTERIZE AND DEFINE SAFE RELIABLE MODULE AND ARRAY DESIGN CONCEPTS AND ASSOCIATED TECHNOLOGY
- CONTINUE TO EVOLVE ANALYTICAL AND EXPERIMENTAL METHODS OF EVALUATING MODULES AND ARRAYS INCORPORATING EXPERIENCE GAINED BY THE PROJECT AND JOE ACTIVITIES

MODULE PERFORMANCE AND FAILURE ANALYSIS

OBJECTIVE
EVALUATE RELIABILITY AND DURABILITY OF MODULES THAT USE MATERIALS AND TECHNIQUES RESEARCHED IN THE PROJECT THROUGH A STRUCTURED PROGRAM

PLANS

- PROCURE MODULE SAMPLES CONSTRUCTED USING INNOVATIVE CONCEPTS
- MEASURE PERFORMANCE CHARACTERISTICS
- IMPLEMENT MEASUREMENT TECHNIQUES NEEDED TO ASSESS MODULE PERFORMANCE IN RESPONSE TO EVOLVING REQUIREMENTS
- PERFORM A BROAD PROGRAM OF ENVIRONMENTAL TESTING IN THE LABORATORY
- PLACE MODULES IN FIELD BITES FOR ENDURANCE TESTING
- CORRELATE FIELD AND LABORATORY TESTING RESULTS TO EVALUATE THE ENVIRONMENTAL TESTING PROGRAM
- PERFORM DIAGNOSTIC ANALYSES OF MODULE PROBLEMS OR FAILURES

FSA Project Meetings

- REDUCE NUMBER OF PIMS PER YEAR
 - TWO IN 1982
 - ONE OR TWO IN 1983
- CONDUCT IN-DEPTH TECHNICAL WORKSHOPS
 - LOW-COST SOLAR ARRAY WAFERING WORKSHOP JUNE 1981
 - SCIENCE OF SILICON MATERIAL PREPARATION AUGUST 1982
 - HIGH-SPEED GROWTH AND CHARACTERIZATION OF CRYSTALS FOR SOLAR CELLS NOVEMBER 1982

Possible Workshops During 1983

- HIGH-EFFICIENCY CRYSTALLINE SILICON SOLAR CELLS
- METALLIZATION FOR HIGH-EFFICIENCY, LONG-LIFE CELLS
- ENCAPSULATION MATERIAL TECHNOLOGY FOR SOLAR CELL MODULES
- TEMPERATURE/HUMIDITY AND ELECTROCHEMICAL CORROSION EFFECTS ON CELL AND MODULE DEGRADATION
- CENTRAL-STATION ARRAY DESIGN CRITICAL PARAMETERS
- ROOF-TOP ARRAY DESIGN CRITICAL PARAMETERS
- ARRAY/POWER CONDITIONER ELECTRICAL INTERFACE DESIGN

UNION CARBIDE CORP. POLYSILICON STATUS AND PLANS

JET PROPULSION LABORATORY

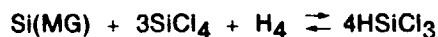
M.H. Leipold ✓

UCC Silane-to-Silicon Process

SEQUENCE OF PROCESS STEPS

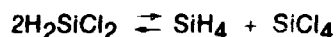
• SILANE SYNTHESIS

• HYDROCHLORINATION:



• REMOVE METAL IMPURITIES AS CHLORIDES

• REDISTRIBUTION $2\text{H SiCl}_3 \rightleftharpoons \text{SiH}_4 + \text{SiCl}_4$



• DISTILLATION/PURIFICATION OF SiH_4 AND CHLOROSILANES

• SILICON CONVERSION (SiH_4 TO Si)

• FLUIDIZED-BED Si DEPOSITION ON SEED PARTICLES (FREE-FLOWING Si PARTICLES $> 300\mu\text{M}$)

• FREE SPACE REACTOR PYROLYSIS AND THEN MELTING/SHOTTING ($> 2 \text{ MM SHOT}$)

• RECYCLING OF H_2 AND SiCl_4

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Contract Progress

- CONTRACT (#954334) STARTED OCTOBER, 1975
- PROCESS FEASIBILITY EXPERIMENTALLY DEMONSTRATED
- SILANE/SILICON PROCESS DESIGN COMPLETED
- COST ESTIMATES INDICATE CAPABILITY OF MEETING THE
<\$14/KG (1980 \$) Si PRICE GOAL
- SILANE SYNTHESIS APPROACH WELL ESTABLISHED
 - NEEDS TO BE TESTED IN CONTINUOUS STEADY-STATE
OPERATION OF EPSDU (EXPERIMENTAL PROCESS SYSTEM
DEVELOPMENT UNIT)
 - ENGINEERING DESIGN COMPLETED
 - EQUIPMENT FOR EPSDU FABRICATED
 - CIVIL CONTRACT AT EAST CHICAGO UCC SITE COMPLETED
 - JPL/DOE FUNDING FOR SILANE SYNTHESIS EPSDU STOPPED
BEFORE MECHANICAL AND ELECTRICAL INSTALLATIONS
- CONVERSION OF SILANE TO SILICON:
 - FLUIDIZED-BED APPROACH APPEARS PROMISING, BUT NEEDS
FURTHER R & D. EFFORT WILL CONTINUE UNDER DOE/JPL
CONTRACT
 - FREE-SPACE REACTOR APPROACH IS LESS FAVORABLE.
MAJOR PROBLEMS IN POWDER HANDLING, MELTING, SHOTTING
OPERATION AND PURITY CONTROL
- CONTRACT MODIFICATIONS ARE UNDERWAY. THESE ARE EXPECTED
TO RESULT IN UCC OPERATING EPSDU AT THEIR EXPENSE WITH
PERFORMANCE RESULTS AVAILABLE TO DOE/JPL

Status: UCC Plans for Polysilicon Production

- ON MAY 1, 1981, UCC ANNOUNCED ITS INTENTION TO BUILD A 1000 MT/YR COMMERCIAL POLY SI PLANT IN WASHINGTON STATE. DESIGN TO BE BASED ON THE DATA FROM THE SILANE EPSDU; KOMATSU (SIEMENS TYPE) DEPOSITION REACTORS
- EPSDU EQUIPMENT MOVED (FROM EAST CHICAGO) AND BEING INSTALLED IN WASHOUGAL, WASHINGTON. THIS IS A UCC PILOT PLANT PROJECT. OPERATION EXPECTED IN FALL 1982 (USING KOMATSU REACTORS)

Future Activities and Prospects

- ADVANCED SILANE SYNTHESIS TECHNOLOGY (FBR) TO BE TESTED IN PILOT PLANT AT UCC ELECTRONIC MATERIALS TEST CENTER AS FINAL PHASE OF JPL/DOE R & D INVESTIGATION
- THE DEVELOPMENT OF SILANE/SILICON PROCESS CONTINUES TOWARD PROVIDING A LOW-COST POLY SI TECHNOLOGY. ALTHOUGH MANY FUNDING/SCHEDULE CHANGES OCCURRED, THE SUCCESSFUL CONTINUATION OF THIS PROGRAM SHOWS THAT THIS APPROACH REPRESENTS AN EFFECTIVE WAY OF CONDUCTING COOPERATIVE ENERGY R & D BY THE INDUSTRY AND THE GOVERNMENT
- FSA/DOE GOAL OF < \$14/KG SILICON CAN ONLY BE ACHIEVED BY SILANE/SILICON PROCESS WHICH INCORPORATES NEW TECHNOLOGY DEPOSITION REACTOR - SUCH AS FBR BEING INVESTIGATED

ADVANCED CZOCHRALSKI INGOT GROWTH

KAYEX CORP.

✓ R.L. Lane

IN TODAY'S MARKET, A VERY HIGH PERCENTAGE OF THE SOLAR CELLS PRODUCED CONTINUE TO BE MADE BY THE CZOCHRALSKI METHOD. TO SOME EXTENT, THE REASON FOR THIS IS INERTIA. CZOCHRALSKI PRODUCTION FACILITIES EXIST WITH KNOWN COSTS AND PREDICTABLE PRODUCT QUALITY. IMPROVEMENTS IN THE PROCESS AS A RESULT OF THE SEMICONDUCTOR INDUSTRY WERE MOST CERTAINLY USED TO ADVANTAGE FOR SOLAR CELL MANUFACTURE.

ON THE OTHER HAND, THE NEWER TECHNOLOGIES - CAST MATERIAL, AMORPHOUS, RIBBONS, ETC. OFFER VERY ATTRACTIVE COST SCENARIOS AND PROJECTIONS. WHY ARE NOT COMPANIES JUMPING INTO THESE NEW TECHNOLOGIES?

IT IS APPARENT THAT, ALTHOUGH GOOD PROGRESS HAS BEEN MADE ON THE MANY ALTERNATIVE METHODS, THE PROGRESS IN ADVANCED CZ HAS ALSO BEEN SIGNIFICANT, AND STILL PRESENTS THE SOLAR SHEET MANUFACTURER WITH A SATISFACTORY RETURN ON INVESTMENT.

INDEED, THE BASIC ADVANCED CZ METHOD I WILL DISCUSS IN THE NEXT FEW MINUTES IS ALREADY IN USE COMMERCIALY FOR SOLAR CELL PRODUCTION. WITHOUT THE DOE FUNDING THROUGH JPL THAT MIGHT NOT BE THE CASE. THE JPL-FUNDED WORK IN THE PAST HAS YIELDED SOME VERY POSITIVE RESULTS. EQUIPMENT AND PROCESSES ARE NOW AVAILABLE TO THE MARKET WHICH SATISFY CERTAIN NEEDS OF THE PV MANUFACTURER, WHICH WOULD NOT HAVE OTHERWISE BEEN FILLED.

THE VARIOUS ADVANCED CZ CONTRACTS SUPPORTED THROUGH JPL WERE NOT OF MUCH INTEREST FOR SEMICONDUCTOR APPLICATIONS. THE WORK WOULD NOT HAVE BEEN PERFORMED, EITHER BY THE SEMICONDUCTOR HOUSES OR THE EQUIPMENT MANUFACTURERS.

PLENARY SESSION: R.L. LANE

WE ARE NOW ENTERING A PERIOD OF DEVELOPMENT WHERE THE SEMICONDUCTOR INDUSTRY WILL MOST DEFINITELY DIVERGE EVEN MORE FROM THE DIRECTION OF THE PHOTOVOLTAIC INDUSTRY. THE SEMICONDUCTOR HOUSES, FOR EXAMPLE, ARE STUDYING INTENSELY SUCH AREAS AS CRYSTAL DEFECT STRUCTURE, OXYGEN CONTROL, AND INTRINSIC CRYSTALLINITY, AND MAGNETIC CRYSTAL GROWTH FOR STRIATION CONTROL. IT IS DIFFICULT TO FIND MUCH RELATIONSHIP OF THESE STUDIES TO PHOTOVOLTAICS.

THE ANSWERS TO PROBLEMS IN PRODUCING PV SILICON INGOTS WILL COME FROM DEVELOPMENTAL WORK WHICH DIRECTLY ADDRESS THOSE PROBLEMS.

IN THIS BRIEF PRESENTATION, I WILL ATTEMPT TO DESCRIBE THE PROGRESS THAT HAS BEEN MADE OVER THE PAST FEW YEARS, THE PRESENT STATUS, AND THE PROBLEM AREAS THAT NEED FURTHER RESEARCH AND DEVELOPMENT.

Cost Components

COMPONENT	ONE CRYSTAL PER CRUCIBLE	150 KG PER CRUCIBLE
EQUIPMENT	18%	40
FACTORY	3	4
LABOR	12	9
UTILITIES	5	12
MATERIALS (62%)		(35%)
CRUCIBLES	48	14
GRAPHITE	8	12
MISC.	6	9
	100%	100%
APPROXIMATE ADD-ON COST	\$80/KG	\$20/KG

RLL APRIL 21, 1982

PLENARY SESSION: R.L. LANE

THE SAMICS/IPEG METHODOLOGY DEVELOPED AT JPL (SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARD/INTERIM PRICE ESTIMATION GUIDELINES) DEFINES FIVE COST ELEMENTS:

EQUIPMENT
FACTORY FLOOR SPACE
DIRECT LABOR
UTILITIES
MATERIALS.

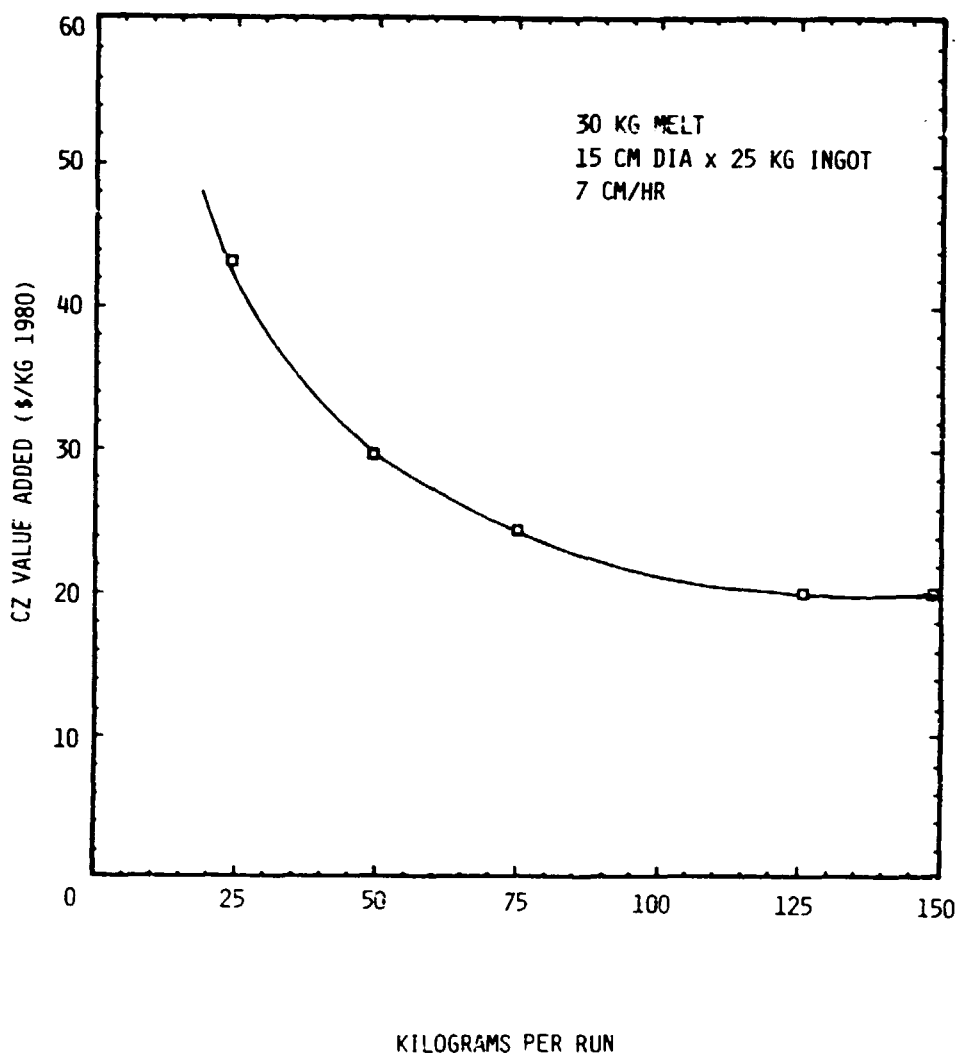
IN THE IPEG PRICE EQUATION, THE PRICE IS PROPORTIONAL TO THE SUM OF THESE ELEMENTS (MULTIPLIED X OVERHEAD) AND, OF COURSE, THE PRICE IS INVERSELY PROPORTIONAL TO THE SPEED AT WHICH THE FACILITY PRODUCES MATERIAL (THE THROUGHPUT). THE INDICATED COST ELEMENTS WERE BELIEVED TO BE THE MOST IMPORTANT.

IT WAS FOUND, BY THE JPL IPEG PRICE CALCULATION, THAT THE STANDARD CZ PROCESS CURRENTLY USED IN THE SEMICONDUCTOR INDUSTRY IS VERY HEAVY ON MATERIAL COST (NOT INCLUDING SILICON). INDEED, 62% IS MATERIAL AND MOST OF THAT IS CRUCIBLE COST ALONE.

IT WAS FURTHER CALCULATED THAT THE CRUCIBLE COST COULD BE REDUCED SIGNIFICANTLY IF ONE COULD GROW LARGE QUANTITIES, UP TO 150 KG, FROM A SINGLE CRUCIBLE. IT IS TO BE EXPECTED, SINCE THE TOTAL MUST BE 100%, THAT A REDUCTION IN THE CRUCIBLE PORTION, WOULD CAUSE OTHER COST ELEMENTS TO INCREASE.

THE NUMBERS INDICATE, HOWEVER, A DRAMATIC INCREASE IN THE COST PORTION ALLOTTED TO EQUIPMENT. ALTHOUGH THE EQUIPMENT REQUIRED TO PRODUCE THE 150 KG IS SUBSTANTIALLY MORE THAN THAT REQUIRED IN THE FIRST COLUMN, IT SHOULD BE NOTED THAT THE ADD-ON COST PER KILOGRAM IN THE SECOND COLUMN IS REDUCED BY A FACTOR OF 4.

Cz Value Added vs Amount Produced From One Crucible



THE SENSITIVITY OF RUN SIZE UP TO 150 KILOGRAMS IS SHOWN IN THIS SLIDE. IT SHOWS A SUBSTANTIAL REDUCTION IN COST BY THE GROWTH OF TWO OR THREE INGOTS FROM ONE CRUCIBLE. THE COST BENEFIT BECOMES MARGINAL IN THE 100-150 KILOGRAM RANGES.

ALTHOUGH THE CRUCIBLE COST PER KILOGRAM CONTINUES TO DECREASE FOR LARGER RUNS, SOME COSTS INCREASE, SUCH AS EQUIPMENT; THUS, THE TOTAL COST LEVELS OUT.

OTHER COST ELEMENTS, SUCH AS UTILITIES AND LABOR, ARE INDEPENDENT OF RUN LENGTH, AND, THUS, INFLUENCE THE CURVE TO LEVEL OUT.

PLENARY SESSION: R.L. LANE

JPL AWARDED CONTRACTS TO FOUR COMPANIES IN 1977 AND DIRECTED THOSE COMPANIES TO DEVELOP WAYS OF REDUCING THE COST OF INGOT-GROWN SILICON. SPECIFIC GOALS WERE TO:

- (1) GROW LARGE QUANTITIES OF SILICON FROM A SINGLE CRUCIBLE
(UP TO 100 KG)
- (2) INCREASE GROWTH RATE TO ACHIEVE HIGHER THROUGHPUT
- (3) MAINTAIN THE HIGH QUALITY OF CZ-GROWN MATERIAL.

ALTHOUGH THE OBJECTIVES WERE THE SAME, THE APPROACHES DIFFERED.

Approaches

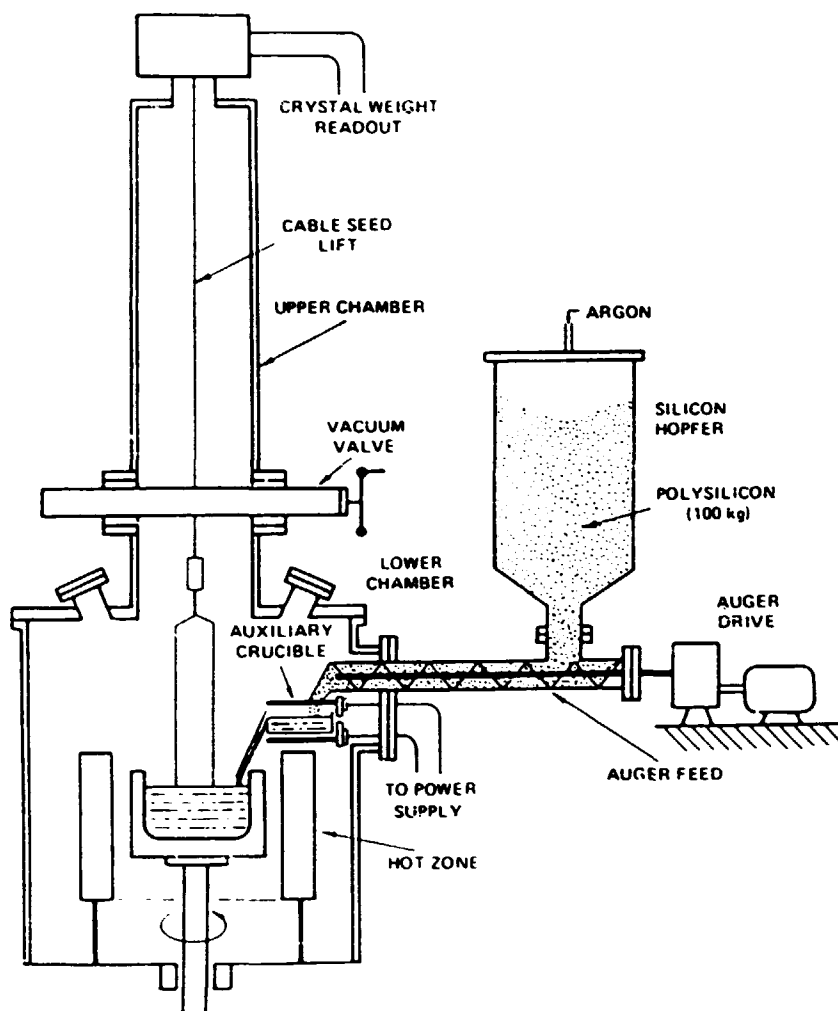
- SILTEC - CONTINUOUS LIQUID FEED FROM SECONDARY MELTING CHAMBER THROUGH A TRANSFER TUBE.
- TEXAS INSTRUMENTS - CONTINUOUS LIQUID FEED.
 AUGER FEED OF LUMP SILICON TO PREMELTER.
- VARIAN - INTERMITTENT GROWTH/RECHARGE CYCLES.
 AUGER FEED OF LUMP SILICON FROM HOPPER.
- KAYEX/HAMCO - INTERMITTENT GROWTH/RECHARGE CYCLES USING
 EITHER POLY-ROD FEED OR DISCHARGE FROM A HOPPER.

SILTEC - DEVELOPED A METHOD OF CONTINUOUS LIQUID FEED FROM A SECONDARY MELTING CHAMBER THROUGH A HEATED TRANSFER TUBE.

TEXAS INSTRUMENTS - ALSO CHOSE TO FEED THE GROWTH CRUCIBLE WITH LIQUID SILICON CONTINUOUSLY DURING GROWTH, BY FEEDING A PREMELTER WITH CHUNK SILICON.

VARIAN AND KAYEX/HAMCO CHOSE TO ADHERE MORE CLOSELY TO THE USUAL GROWTH METHODS, THUS REQUIRING INTERMITTENT RECHARGE AND MELTING CYCLES. THESE TWO CONTRACTORS ONLY DIFFERED IN THEIR MECHANICAL MEANS TO INSERT THE SILICON INTO THE HOT CRUCIBLE.

Continuous Cz Silicon Furnace (Texas Instruments)



IN THE T.I. SYSTEM, THE AUGER FEEDER INTRODUCED SILICON INTO A SMALL PREMELTER. THE LIQUID SILICON THEN FLOWED INTO THE CRUCIBLE, THEREBY MAINTAINING A CONSTANT MELT LEVEL DURING GROWTH.

IF THE LIQUID TEMPERATURE WERE REASONABLY CONTROLLED, IT WAS EXPECTED THAT THERE WOULD BE NO HARMFUL THERMAL PERTURBATION OF THE MELT. INGOT SIZE WOULD ONLY BE LIMITED BY THE PULL LENGTH OF THE EQUIPMENT.

IT WAS FOUND THAT THE OPERATION OF THE PREMELTER WAS A VERY DIFFICULT TASK, PRIMARILY BECAUSE (1) THE REFRACTORY QUARTZ LINER OF THE PREMELTER DEVITRIFIED RAPIDLY, AND (2) THE UNIFORM FLOW OF SILICON WAS NEARLY IMPOSSIBLE DUE TO THE HIGH SURFACE TENSION OF THE LIQUID. CONSIDERABLE EFFORT WAS MADE ON PREMELTER DESIGN.

PLENARY SESSION: R.L. LANE

ALSO, T.I. REPORTED THAT THE AUGER FEED SYSTEM WORKED POORLY FOR CHUNK SILICON, AS IT TENDED TO CRUSH THE SILICON. CONCERN WAS EXPRESSED THAT THE ABRASIVE NATURE OF SILICON WAS PROBABLY CAUSING CONTAMINATION OF THE SILICON FROM THE STAINLESS STEEL AUGER.

THE T.I. WORK, HOWEVER, WAS SIGNIFICANT, IN THAT IT ILLUSTRATED THE EXTREME DIFFICULTY IN HANDLING BOTH SOLID AND LIQUID SILICON IN A CONTROLLED MANNER WITHOUT CONTAMINATION.

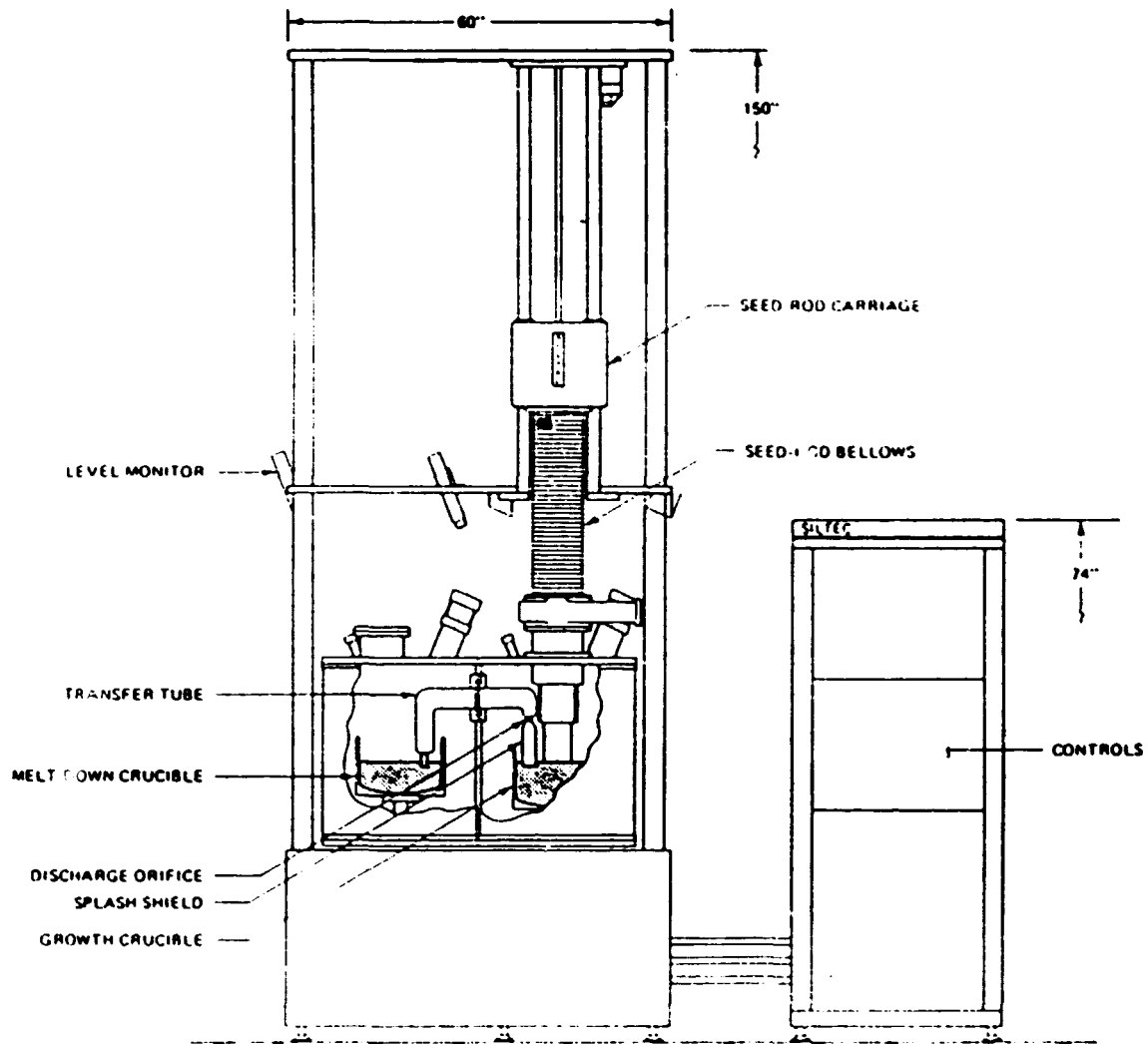
THE VARIAN SYSTEM WAS QUITE SIMILAR TO THE T.I. EXCEPT THAT RECHARGING WAS PERFORMED INTERMITTENTLY BETWEEN INGOT GROWTH CYCLES. THE AUGER SYSTEM WAS ADAPTED TO FEED LUMP SILICON DIRECTLY INTO THE CRUCIBLE.

VARIAN HAD GOOD SUCCESS WITH THIS RECHARGING SYSTEM AND REPORTED SEVERAL FAIRLY LARGE RUNS COMPLETED; UP TO ABOUT 60-70 KILOGRAMS.

PERHAPS ONE OF THE MOST VALUABLE RESULTS FROM THE VARIAN WORK WAS AN EXPERIMENT PERFORMED VERY EARLY IN THE JPL PROGRAM. A 100 KG RUN SIMULATION WAS PERFORMED, BY THE GROWTH OF FIVE 20 KG INGOTS SEQUENTIALLY FROM THE SAME CRUCIBLE AND SAME CHARGE OF SILICON. AFTER EACH INGOT WAS GROWN, IT WAS REMELTED INTO THE CRUCIBLE AND THE CYCLE WAS REPEATED.

THIS EXPERIMENT PROVED THAT THE CRUCIBLE WOULD SURVIVE FOR LONG PERIODS OF TIME THROUGH SEVERE THERMAL CYCLING. IT WAS AN ENCOURAGING RESULT FOR ALL CONTRACTORS.

Siltec Continuous Liquid-Feed Furnace



PLENARY SESSION: R.L. LANE

THE SILTEC EFFORT WAS VERY SIGNIFICANT IN THAT IT POINTED OUT A WAY TO OVERCOME OR AVOID THE EFFECT OF THE HIGH SURFACE TENSION ON THE POURING OF SILICON. A SIPHON PRINCIPLE WAS USED. ONCE THE TRANSFER TUBE WAS FILLED WITH LIQUID, UNIFORM AND CONTINUOUS FLOW COULD BE ACHIEVED BY SIMPLY RAISING THE LEVEL OF THE SUPPLY CRUCIBLE.

SIMULTANEOUS CRYSTAL GROWTH AND CONTINUOUS LIQUID FEED REPLENISHMENT WERE DEMONSTRATED. ALSO, THE POSSIBILITY OF GROWING AN EXTREMELY LARGE INGOT FROM A RELATIVELY SMALL CRUCIBLE WAS DEMONSTRATED BY THE GROWTH OF AN INGOT OF OVER 60 KG.

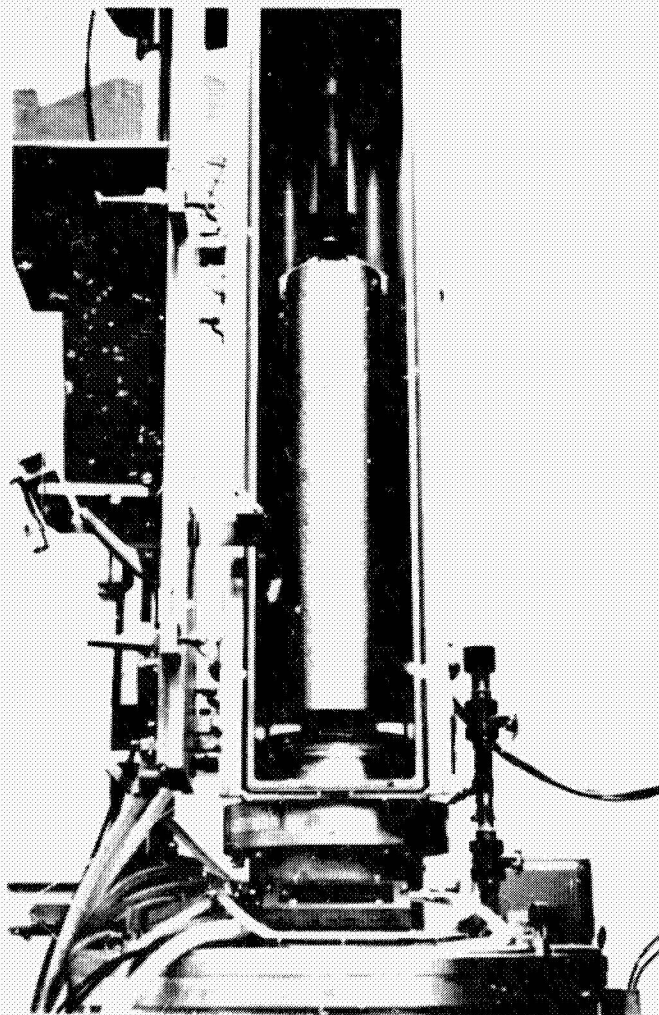
ALTHOUGH THE SILTEC METHOD IS NOT WELL ENOUGH DEVELOPED FOR COMMERCIAL APPLICATION, ITS POTENTIAL FOR LOW COST INGOT GROWTH PROBABLY SURPASSES THE OTHER APPROACHES, PRIMARILY BECAUSE ITS THROUGHPUT SHOULD BE THE HIGHEST.

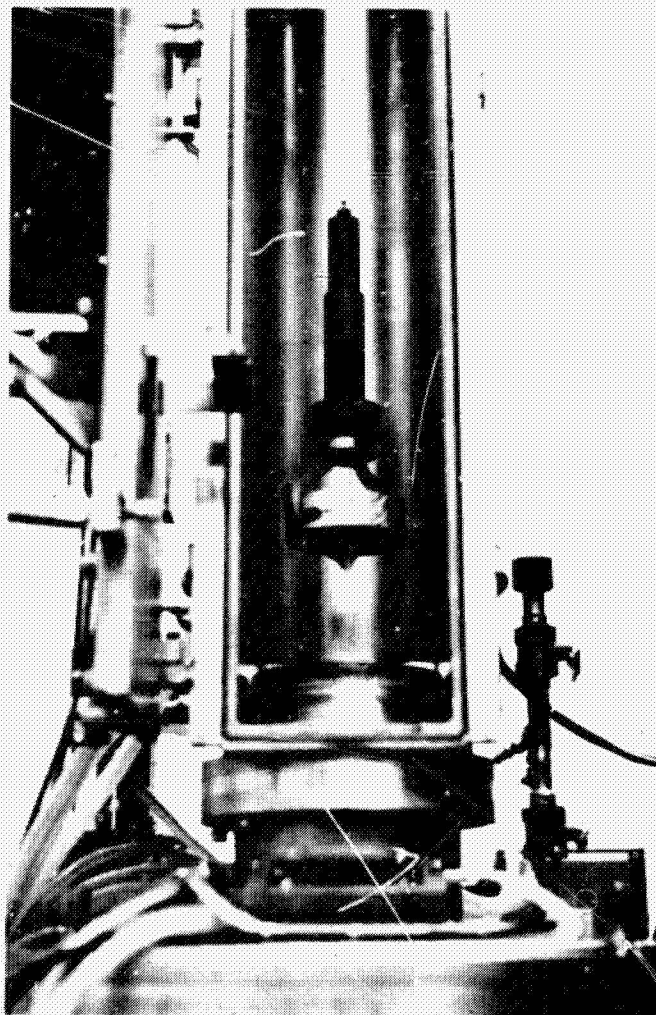
THE DEMONSTRATION OF CONTINUOUS LIQUID FEED WAS AN EXCELLENT TECHNICAL ACCOMPLISHMENT AND MAY VERY WELL HAVE A SIGNIFICANT FUTURE APPLICATION.

KAYEX CORPORATION'S HAMCO DIVISION, A MANUFACTURER OF CRYSTAL GROWERS AND OTHER SILICON PROCESSING EQUIPMENT, HAD PERHAPS THE MOST SIMPLE-MINDED APPROACH OF ALL. RATHER THAN HAVING COMPLICATED RECHARGING OR PREMELTING EQUIPMENT, IT WOULD SIMPLY PROVIDE FOR STORAGE OF A QUANTITY OF SILICA WITHIN THE VACUUM TIGHT GROWTH CHAMBER. THE SILICON FEED STOCK COULD BE EITHER LUMP OR ROD FORM. THE CHAMBER COULD BE RELOADED WITH SILICON FEED STOCK AT THE TIME OF CRYSTAL REMOVAL, THEREBY ELIMINATING A PUMPDOWN/PURGE CYCLE.

ALTHOUGH IT WAS OBVIOUS THAT RECHARGING WITH LUMP SILICON PRECLUDED CONTINUOUS GROWTH AND ALSO LIMITED ULTIMATE THROUGHPUT, THE METHOD DID OFFER A SHORTER-TERM APPROACH TO COMMERCIALIZATION.

IF THE RECHARGE METHOD COULD BE MADE SAFE AND RELIABLE, IT WOULD HAVE A SIGNIFICANT IMPACT ON COST.

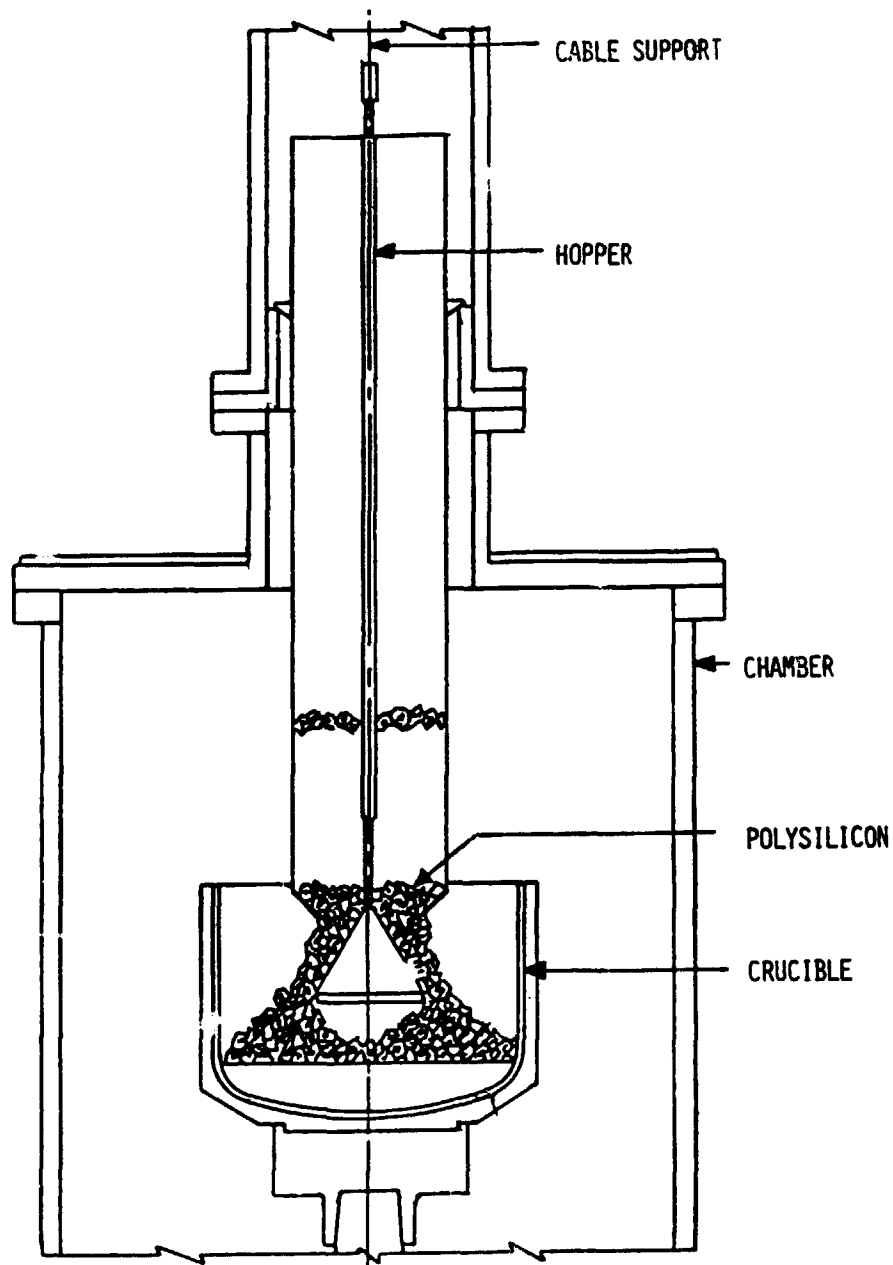




IT BECAME APPARENT THAT THE USE OF POLY RODS AS RECHARGE FEEDSTOCK
HAD SOME SERIOUS DISADVANTAGES:

- (1) RODS COULD NOT ^{always} BE OBTAINED CRACK-FREE; NEITHER COULD THEY BE
DEPENDENT UPON TO SURVIVE THE THERMAL SHOCK DURING RECHARGING.
- (2) SUITABLE RODS WERE MORE EXPENSIVE THAN CHUNK SILICON.
- (3) THE MELTING RATE WAS ^{rather} SLOW, AND REQUIRED EXCESSIVE HEATING OF THE
CRUCIBLE AND MELT
- (4) OPERATOR ATTENTION WAS REQUIRED, AND, OF COURSE, RODS COULD NOT
BE COMPLETELY MELTED.

Poly Chunk Recharge System



A SELF-DUMPING HOPPER WAS THEREFORE DESIGNED AND BUILT WHICH HAD ABOUT A 16 KILOGRAM CAPACITY. IT WAS A SIMPLE DESIGN AND QUICKLY BECAME THE PREFERRED METHOD. AS THE HOPPER IS LOWERED, IT COMES TO REST ON A RING AT THE ISOLATION VALVE. THE PLUG SUPPORTING THE CHARGE AT THE BOTTOM OF THE HOPPER CONTINUES TO LOWER AS THE SUPPORTING CABLE IS LOWERED, EFFECTING COMPLETE DISCHARGE OF THE SILICON.

PLENARY SESSION: R.L. LANE

THE HOPPER CAN BE LOWERED AND DISCHARGED IN ABOUT 5 MINUTES. SEVERAL HOPPER-FULLS CAN BE DUMPED DURING A MELTING CYCLE. NO FAILURES HAVE BEEN EXPERIENCED WITH EITHER THE HOPPER OR THE CRUCIBLE DURING MANY RECHARGE CYCLES OVER THE PAST SEVERAL YEARS.

MELT-BACK IS FASTER THAN ROD, NO TIME IS WASTED BY MULTIPLE DUMPS, AND NO CONTAMINATION HAS BEEN DETECTED FROM THE HOPPER. CHUNK SIZE IS LIMITED TO A MAXIMUM DIMENSION OF ABOUT 1 INCH.

Advanced Cz Objectives

	<u>INITIAL</u>	<u>LATEST</u>
RUN SIZE (ONE CRUCIBLE)	100 KG	150 KG
DIAMETER	10 CM	15 CM
GROWTH RATE	10 CM/HR	10 CM/HR
MELT SIZE	25 KG	45 KG
INGOT SIZE	5 x 20 KG	4 x 37.5 KG
MELT RATE	-	25 KG/HR
AUTOMATION	ANALOG	MICROPROCESSOR
AFTER GROWTH YIELD	90%	90%
AM-1 EFFICIENCY	14%	14%

AS PROGRESS WAS MADE IN ADVANCED CZ, THE INITIAL OBJECTIVES WERE MODIFIED, AS SHOWN IN THIS SLIDE. 100 KILOGRAM RUN SIZE WAS INCREASED TO 150 KG; DIAMETER INCREASED FROM 10 TO 15 CM. GROWTH RATE GOALS WERE KEPT THE SAME FOR THE HIGHER DIAMETERS. MELT SIZE INCREASED, AND NEW GOALS WERE DEFINED TO IMPROVE THROUGHPUT AND LOWER COSTS, THAT IS, MORE RAPID MELTDOWN, AND MICROPROCESSOR CONTROL TO REDUCE LABOR. YIELDS AND SOLAR EFFICIENCY GOALS HAVE REMAINED CONSTANT FROM THE BEGINNING AT 90% YIELD AND 14% AM-1, RESPECTIVELY.

Continuous Cz Growth Summary

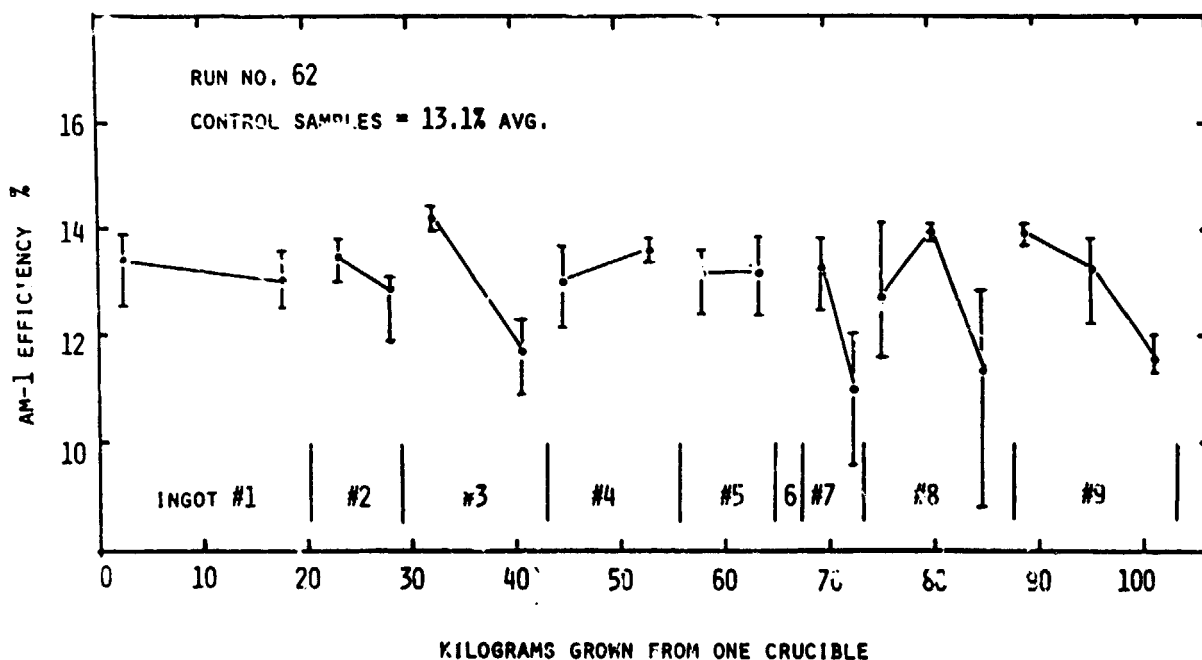
DATE	RUN NO.	TOTAL PULLED (KG)	NO. OF INGOTS	DIAMETER (CM)	AVG. PULL RATE (CM/HR)	RUN TIME (HR)	THROUGH-PUT (KG/HR)	MONO-CRYSTAL (%)	AM-1 EFFICIENCY, %		
									RUN AVG	MONO-CRYSTAL	POLY CRYSTAL
4/78	9	27	3	11	8.7	39	0.70	85	11.5	11.6	11.4
6/78	11	43	4	11	9.1	44	0.97	88	11.8	11.9	11.2
10/78	19	57	6	13	8.9	64	0.89	56	11.8	-	-
1/79	30	99	6	13	8.7	79	1.25	27	11.2	13.3	9.8
6/79	47	60	5	13	6.8	52	1.17	88	13.0	13.0	-
7/79	49	108	9	13	7.0	86	1.26	85	13.8	13.8	-
10/79	55	101	10	13	7.2	91	1.11	75	12.0	13.0	9.7
10/79	2	100	9	13	7.7	109	0.92	64	12.3	12.7	10.6
12/79	60	100	8	13	7.6	85	1.18	61	12.0	13.0	11.0
1/80	62	103	9	13	7.9	97	1.06	89	12.9	13.2	11.2
2/80	70	152	6	15	6.9	99	1.53	44	-	-	-
6/81	10	146	5	15	5.6	100	1.46	52	13.7	15.3	12.3

THIS TABLE SUMMARIZES THE RESULTS FROM THE MOST SIGNIFICANT RUNS PERFORMED ON THE PROGRAM.

- THE COLUMN LABELED "TOTAL PULLED" IS THE SUM OF ALL INGOT WEIGHTS FOR A GIVEN RUN. THE GRADUAL INCREASE IN RUN SIZE SINCE THE BEGINNING OF THE PROGRAM IS APPARENT.
- "NO. OF INGOTS" - IN MANY RUNS, WE ATTEMPTED TO PRODUCE AS HIGH A YIELD OF MONOCRYSTAL AS POSSIBLE; THUS, INGOTS WERE OFTEN PREMATURELY ABORTED AND SOME RUNS PRODUCED AS MANY AS 9 OR 10 INGOTS. MORE RECENTLY, WE HAVE TRIED TO PRODUCE THE DESIRED NO. OF INGOTS.
- "DIAMETER" - EARLY RUNS WERE 10 CM. THE DIAMETER WAS INCREASED TO 14 CM WITH NO SIGNIFICANT PROBLEMS.

- "AVERAGE PULL RATE" - THE GOAL OF ALL THE WORK IS 10 CM/HR, REGARDLESS OF DIAMETER. THE PULL RATE (OR GROWTH RATE) IS LIMITED AT PRESENT BY THE TENDENCY OF THE CRYSTAL TO GO OUT OF SHAPE. LARGER CRYSTALS MUST BE GROWN SLOWER, ALTHOUGH THE SOLIDIFICATION RATE (KG/HR) IS STILL LARGER.
- "RUN TIME" IS TOTAL RUN TIME FROM START UP TO SHUT OFF.
- "THROUGHPUT" IS OBTAINED BY DIVIDING THE TOTAL PULLED BY THE RUN TIME IN HOURS. IT INCREASES, AS SHOWN, WITH DIAMETER. THE LATEST GOAL IS 2.5 KG/HR, WHICH MAY BE OUR MOST DIFFICULT PROBLEM.
- "PERCENT MONOCRYSTAL" - REPRESENTS THE PORTION OF THE PULLED MATERIAL THAT IS MONOCRYSTALLINE IN STRUCTURE BY VISUAL OBSERVATION. 50-80 KG OF MONOCRYSTAL CAN BE GROWN FROM A CRUCIBLE PRESENTLY.
- "AM-1 EFFICIENCY" IS FOR TEST CELLS PREPARED AND MEASURED BY APPLIED SOLAR.

Solar Efficiency vs kg Grown



PLENARY SESSION: R.L. LANE

ORIGINAL
OF POOR QUALITY

Run No. 62 (100 kg)

- SAMPLES WERE CUT FROM THE TOP AND BOTTOM OF EACH OF THE SMALLER INGOTS AND THE TOP, CENTER AND BOTTOM OF THE LARGER INGOTS.
- FOUR 2 X 2 CM CELLS WERE MADE FROM EACH SAMPLE.
- THE AVERAGE OF THE FOUR CELLS AND THE SPREAD WAS PLOTTED.
- EFFICIENCY IS PLOTTED ON THE ORDINATE, CUMULATIVE AMOUNT GROWN ON THE ABSCISSA.
- THE POINTS FROM THE SAME TREAT ARE CONNECTED FOR CLARITY.

THE CONCLUSIONS:

- POLYCRYSTALLINE MATERIAL WAS LESS EFFICIENT THAN THE SINGLE CRYSTAL.
- EFFICIENCY VALUES FROM THE SAME SAMPLE VARIED AS MUCH AS 1 OR 2 PERCENTAGE POINTS - PROBABLY DUE TO CELL MANUFACTURE.
- EFFICIENCY OF SINGLE CRYSTAL MATERIAL WAS AS GOOD AS, OR BETTER THAN, THE CONTROL SAMPLES.
- EFFICIENCIES REMAINED CONSTANT RIGHT OUT TO 100 KG.
- AVERAGE OF ALL SAMPLES WAS 12.9%.

C-2

PLENARY SESSION: R.L. LANE

Run No. 10 (150 kg)

- SAMPLES WERE CUT FROM THE TOP, CENTER, AND BOTTOM OF ALL INGOTS.
- EXCEPT FOR THE FIRST INGOT, THE BOTTOMS OF ALL CRYSTALS WERE POLY, THE TOPS WERE ALL SINGLE.
- EFFICIENCY OF MONOCRYSTAL WAS SURPRISINGLY CONSTANT AND ALL ABOVE 15%, AVERAGING 15.3%.
- EFFICIENCY OF POLY WAS IN THE 11-13% RANGE AND ALSO CONSTANT TO 150 KG, AVERAGING 12.3%.
- THE INCREASE IN EFFICIENCY COMPARED TO THE PREVIOUS R'M IS BELIEVED TO BE A DIFFERENCE IN THE CELL ^{PAR} ~~JOB~~ TECHNIQUE, AS THE CONTROL CELLS WERE ALSO HIGHER EFFICIENCIES AND THE CONTROL CELLS MEASURED VERY CLOSE TO THE SINGLE CRYSTAL MATERIAL.

PLENARY SESSION: R.L. LANE

Control System: Microprocessor Controls

ONE OF THE GOALS OF THE PROGRAM WAS TO PRODUCE CRYSTAL GROWTH EQUIPMENT WITH MICROPROCESSOR AUTOMATION FOR IMPROVED YIELDS WITH LESS LABOR.

THE PROTOTYPE EQUIPMENT PRODUCED ON THIS WORK WAS RETROFITTED WITH A HANCO AUTOMATIC GROWER LOGIC SYSTEM. IN A PARALLEL EFFORT, IMPROVED SENSORS WERE DEVELOPED ON THE CONTRACT FOR:

- (1) MELT SEEDING TEMPERATURE
- (2) DIAMETER AND SHOULDER SENSOR
- (3) MELTBACK SENSOR.

ALTHOUGH THE SYSTEM IS STILL NOT AN OPERATOR "HANDS OFF" ONE, THE OPERATOR INPUT HAS BEEN REDUCED, AND WE BELIEVE WE HAVE MADE GOOD PROGRESS TOWARD IMPROVED AUTOMATION.

THE MELT TEMPERATURE AND DIAMETER/SHOULDER SENSORS ARE INTERFACED WITH THE MICROPROCESSOR AND ARE USED ON ALL RUNS. THE MELT LEVEL SENSOR IS SET UP TO MONITOR MELT LEVEL, BUT IS NOT ACTUALLY USED IN CLOSED LOOP CONTROL YET.

Problems and Concerns

PROBLEM AREA

- YIELD OF MONOCRYSTAL, LOWER EFFICIENCY OF POLY MATERIAL

- THROUGHPUT AS RELATED TO RATE LIMITING FACTORS

- MELTING RATE
- CORKSCREWING
- STABILIZATION OF MELT TEMPERATURE

APPROACH

- STUDY STRUCTURE LOSS MECHANISMS, PRIMARILY MELT CONTAMINATION

- CRUCIBLE DISSOLUTION
- CRUCIBLE DEVITRIFICATION
- GAS AMBIENT PURITY & FLOW

- IMPROVE HOT ZONE DESIGN

- FURTHER WORK WITH RADIATION SHIELDING
- TEMPERATURE PROFILING OF MELT
- IMPROVED TUNING OF MICROPROCESSOR TO SPEED UP STABILIZATION, SEEDING AND NECKING

IN ATTEMPTING TO EXPRESS PROBLEMS IN SOME MEANINGFUL WAY, I FINALLY CAME UP WITH TWO GENERALIZED PROBLEM AREAS, WHICH ARE LIMITING OUR ABILITY TO ACHIEVE THE PREDETERMINED GOALS; THESE ARE:

- (1) YIELD OF MONOCRYSTALLINE MATERIAL, AND
- (2) THROUGHPUT.

YIELD - IF THE MATERIAL COULD BE ALL PRODUCED IN MONOCRYSTALLINE FORM, THEN IT IS APPARENT THAT SOLAR EFFICIENCIES WOULD BE HIGHER.

STRUCTURE LOSS IS BELIEVED TO BE CAUSED BY CONTAMINATION OF THE MELT, EITHER BY PARTICLES FROM THE CRUCIBLE OR BY CARBON CONTAMINATION FROM THE CARBON MONOXIDE FURNACE GAS ATMOSPHERE.

THROUGHPUT CAN BE INCREASED BY INCREASING THE SPEED OF THE NON-GROWTH OPERATIONS, AS WELL AS THE GROWTH RATE.

- PRESENTLY, THE MELTING RATE DOES NOT MEET OUR GOALS. BECAUSE A CRYSTAL GROWER IS DESIGNED FOR HIGH THERMAL GRADIENTS AND LARGE HEAT LOSSES ABOVE THE MELT, THE MELTING RATE IS LIMITED AND MUCH HEAT IS LOST. PRELIMINARY EXPERIMENTS SHOW THAT TEMPORARY RADIATION SHIELDING OVER THE CRUCIBLE DURING MELTING WOULD SPEED UP THE MELTING RATE WHILE, AT THE SAME TIME, REDUCE POWER CONSUMPTION.

PLENARY SESSION: R.L. LANE

- THE GROWTH RATE IS NOT LIMITED BY STRUCTURE LOSS CONSIDERATIONS; RATHER, IT IS LIMITED BY THE TENDENCY OF CRYSTALS TO LOSE CYLINDRICAL SHAPE - WHICH WE CALL CORKSCREWING. A NUMBER OF RUNS WITH A CONE-SHAPED RADIATION SHIELD HAVE GIVEN ENCOURAGING RESULTS; HOWEVER, THE PROBLEM HAS NOT BEEN ELIMINATED. IT MAY BE THAT STEEPER THERMAL GRADIENTS WILL BE REQUIRED TO PREVENT CORKSCREWING AND, THUS, HOT ZONE REDESIGN MAY BE REQUIRED. WE BELIEVE THAT QUANTITATIVE MEASUREMENTS OF MELT TEMPERATURE GRADIENTS AS A FUNCTION OF VARIABLE GROWTH PARAMETERS WOULD LEAD THE WAY TOWARD IMPROVED THERMAL CONDITIONS FOR FASTER GROWTH AND STRAIGHTER CRYSTALS.
- ALTHOUGH THE MICROPROCESSOR IS CAPABLE OF STABILIZING THE MELT REPRODUCIBLY, IT ACTUALLY TAKES MORE TIME PRESENTLY THAN AN EXPERIENCED OPERATOR. MORE SOFTWARE DEVELOPMENT WILL BE REQUIRED TO IMPROVE THIS SITUATION.

Devitrification



THIS SLIDE SHOWS THE INSIDE SURFACE OF A TYPICAL CRUCIBLE AFTER ABOUT 100 HOURS OF EXPOSURE TO MOLTEN SILICON. IT IS COVERED WITH "ROSETTES" - APPROXIMATELY 1 MM DIAMETER AREAS OF CRYSTALLIZED SiO_2 . IT IS β CRYSTOBALITE, THE STABLE FORM OF QUARTZ AT THAT TEMPERATURE.

THE ROSETTES TEND TO MULTIPLY, PROBABLY BY SOME FORM OF NUCLEATION, EVENTUALLY COVERING THE COMPLETE INNER SURFACE OF THE CRUCIBLE. IF THEIR RATE OF NUCLEATION AND GROWTH IS EXCEEDED BY ^{their} DISSOLUTION, COMPLETE COVERAGE MAY NOT OCCUR. IN FACT, IN THE GLASSY AREAS (BLUE), THERE APPEARS TO BE SOME ^{AREAS} ~~ROSETTES~~ ^{ROSETTES} REMAINS OF ~~ROSETTES~~, NOW TOTALLY DISSOLVED.

ALSO, ONE CAN SEE DARK SPOTS. THESE ARE SIMPLY ~~VOIDS~~ IN THE CRUCIBLE (BUBBLES) FORMED DURING ITS MANUFACTURE, WHICH HAVE BECOME FILLED WITH SILICON.

DEVITRIFICATION AND EXPOSED BUBBLES ARE OF CONSIDERABLE CONCERN BECAUSE THEY ARE POTENTIAL SOURCES OF SiO_2 PARTICULATE MATTER, WHICH, IF IT ENTERS THE CRYSTAL GROWTH INTERFACE, WILL CAUSE STRUCTURE LOSS.



A CLOSER LOOK AT THESE DEVITRIFICATION ROSETTES WITH THE SCANNING ELECTRON MICROSCOPE IS SHOWN IN THIS SLIDE. THERE ARE A NUMBER OF OBSERVATIONS THAT CAN BE MADE:

- (1) THEY ARE FRACTURED AND FLAKING OFF, INDICATING THEIR DIFFERENCE IN STRUCTURE FROM THE GLASSY SURROUNDING AREAS.
- (2) THE ROSETTES ARE ROUND, INDICATING THAT THEY "GROW" OUT FROM A CENTER.
- (3) THE CENTER NUCLEUS HAS MANY SMALL BUBBLES SURROUNDING A RELATIVELY CLEAN AREA.
- (4) A MAGNIFIED AREA AT THE EDGE SHOWS THAT THE EDGE APPEARS TO BE LIFTED FROM THE BULK MATERIAL, AND THE ROSETTE APPEARS TO HAVE GROWN INTO THE BULK AS WELL AS Laterally.

PLENARY SESSION: R.L. LANE

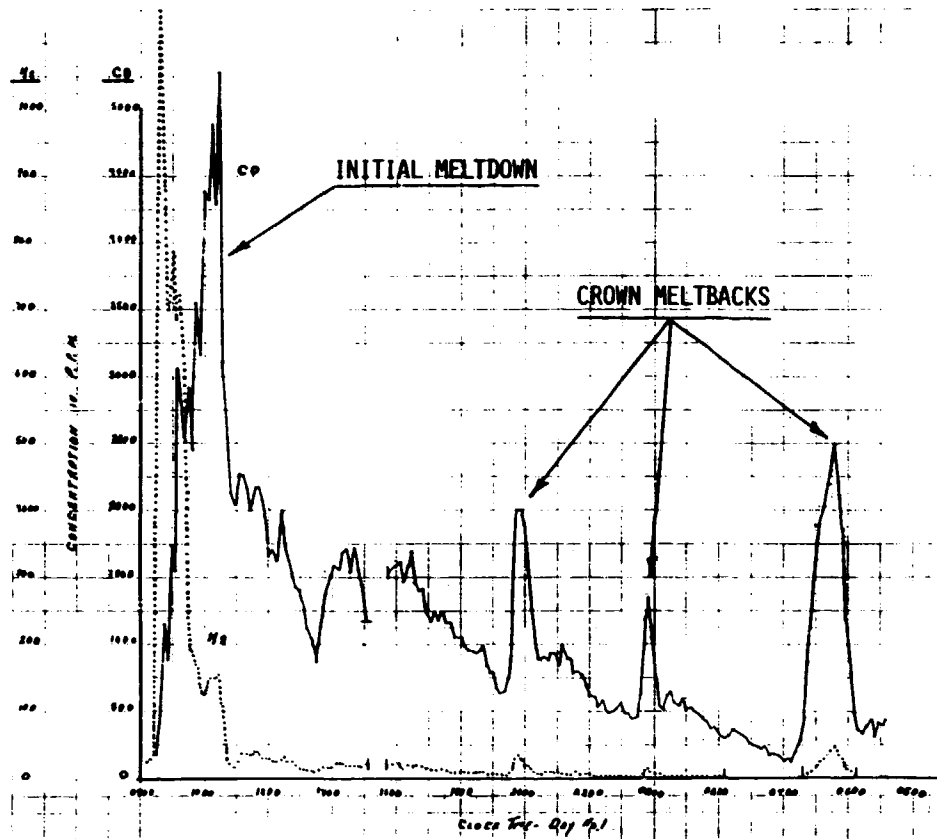
(5) ENERGY DISPERSIVE X-RAY ANALYSIS SHOWS ONLY SILICON WITH NO DETECTABLE IMPURITIES IN (A) THE BULK SiO_2 AND (B) THE INTERNAL PORTIONS OF THE ROSETTES. HOWEVER, RIGHT AT THE EDGE, SURPRISINGLY HIGH CONCENTRATIONS OF METAL ARE DETECTED.

EXPRESSED AS ATOMIC PERCENT:

SI	89.92
S	1.78
CL	5.01
K	2.15
CA	1.14

WE BELIEVE THAT THIS DEVITRIFICATION IS ASSOCIATED WITH LOSS OF MONOCRYSTALLINITY. WE ALSO BELIEVE THAT IT IS ACCELERATED BY IMPURITIES IN CRUCIBLE, MELT, ON FURNACE.

CO and H₂ vs Run Time



IN AN ATTEMPT TO UNDERSTAND THE MECHANISM OF STRUCTURE LOSS, WE HAVE CONSTRUCTED A DEVICE WHICH SAMPLES AND ANALYZES THE GROWER EXHAUST GAS FOR CARBON MONOXIDE, HYDROGEN, AND WATER. IF CARBON IS CONTAMINATING THE MELT, IT WILL BE CONCENTRATED IN THE RESIDUAL MELT AND COULD LEAD SUBSEQUENTLY TO SILICON CARBIDE PRECIPITATION, AS MORE AND MORE CRYSTALS ARE GROWN.

CARBON MONOXIDE HAS BEEN FOUND IN SURPRISINGLY HIGH CONCENTRATIONS, AND IS A FUNCTION OF TEMPERATURE.

DESCRIBE PLOT -

- SCALES, ORDINATE & ABSCISSA
- CO AND H₂
- MELTBACKS VS. RECHARGE
- TREND DOWNWARD WITH TIME

APPROXIMATELY 5000 PPM ARE SEEN DURING MELTDOWN.

H₂ EVOLUTION AND WATER (NOT SHOWN) REACT LIKE TYPICAL OUTGASSING.

Advanced Cz Status

GOALS ACHIEVED

150 KG FROM ONE CRUCIBLE (5 x 30 KG INGOTS)
15 CM DIAMETER x 37.5 KG GROWTH DEMONSTRATED
MICROPROCESSOR CONTROLS WITH IMPROVED SENSORS
PROTOTYPE EQUIPMENT TRANSFERRABLE TO INDUSTRY
AFTER-GROWTH YIELD - 90% OF MELT PULLED
14% AM-1 IN MONOCRYSTAL

GOALS NOT ACHIEVED

THROUGHPUT - 2.5 KG/HR
YIELD OF MONOCRYSTAL - 90%
RECHARGE MELTING RATE - 25 KG/HR

DEMONSTRATED

1.5 KG/HR FOR 150 KG RUN
50% MONO 150 KG
14 KG/HR

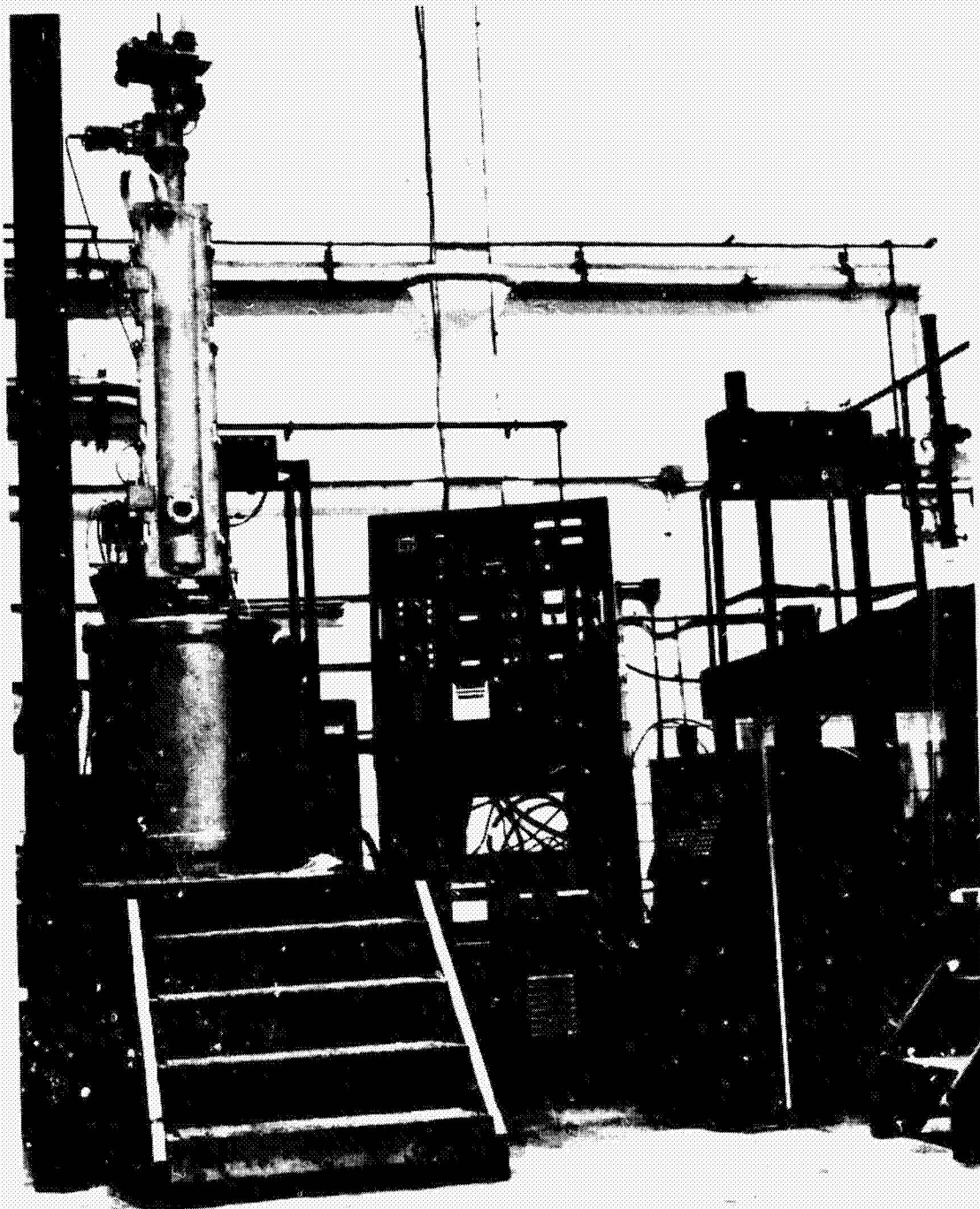
TO SUMMARIZE THE STATUS, WE HAVE MADE A LARGE NUMBER OF MULTIPLE INGOT RUNS WITH RUN SIZE UP TO 150 KILOGRAMS. THE RECHARGE PROCEDURE IS RELIABLE FROM A PRODUCTION STANDPOINT.

- 30 KG INGOTS HAVE BEEN PRODUCED IN 150 KG RUNS, AND THE FEASIBILITY OF EVEN LARGER INGOTS HAS BEEN ESTABLISHED ON THE JPL FACILITY.
- THE MICROPROCESSOR SYSTEM REQUIRES MORE SOFTWARE DEVELOPMENT, BUT HAS THE POTENTIAL TO LOWER LABOR COST AND IMPROVE PERFORMANCE.
- KAYEX RECENTLY HAS INTRODUCED THE HAMCO CG6000 CRYSTAL GROWER WITH A CHARGE CAPACITY IN THE 50-60 KILOGRAM RANGE, WHOSE DESIGN IS BASED UPON THE JPL PROTOTYPE. THUS, THE LATEST TECHNOLOGY IS NOW AVAILABLE TO THE INDUSTRY.
- CERTAIN IMPORTANT GOALS WERE NOT COMPLETELY ACHIEVED.
- SELECTIVE R & D PROGRAMS, AS SUGGESTED, WOULD ADDRESS THESE GOALS:
 - THROUGHPUT - RADIATION SHIELDING, TEMPERATURE PROFILING.
 - YIELD - CRUCIBLE AND GAS ANALYSES.
 - RECHARGE MELTING RATE - TEMPORARY RADIATION SHIELDING DURING MELTING.

PLENARY SESSION: R.L. LANE

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

CG6000



THIS IS A PHOTOGRAPH OF THE FIRST CG6000 WHEN IT WAS BEING ASSEMBLED. THIS MACHINE WAS PURCHASED SPECIFICALLY FOR SOLAR INGOT PRODUCTION USING THE JPL-DEVELOPED PERIODIC RECHARGE METHOD. IT IS PLANNED TO PRODUCE 60 TO 80 KILOGRAMS FROM EACH CRUCIBLE. ALTHOUGH THIS IS NOT THE QUANTITY DEEMED TO BE THE MOST COST EFFECTIVE, IT IS CERTAINLY A MAJOR STEP TOWARD LOWER COST SOLAR GRADE MATERIAL.

PLENARY SESSION: R.L. LANE

I WOULD LIKE TO SUMMARIZE BY EXPLAINING OUR POSITION WITH RESPECT TO GROWTH EQUIPMENT.

- FIRST, THE CZ PROCESS, WITHOUT QUESTION, IS CAPABLE OF PRODUCING CONSISTENTLY THE HIGHEST EFFICIENCY PHOTOVOLTAIC CELLS.
- HIGH EFFICIENCY IS A VERY IMPORTANT INGREDIENT TO LOW COST, BECAUSE LESS OF ALL OTHER MATERIALS ARE REQUIRED TO PRODUCE A KILOWATT OF POWER - LESS GLASS, LESS STRUCTURE, LESS SILICON, EVEN LESS REAL ESTATE.
- SECONDLY, IT IS FAST. EVEN AT 1.4 KG/HR, IT IS EQUIVALENT TO OVER $1 \text{ m}^2/\text{HR}$ FOR ONE PULLER, WHICH IS ABOUT 100 WATTS OF GENERATING CAPACITY PER HOUR. IT TAKES 6 TO 7 OF THE FASTEST RIBBON PULLERS TO KEEP UP WITH ONE CZOCHRALSKI PULLER IN TERMS OF SQUARE METERS PER HOUR.
- AS A THIRD POINT NOT MENTIONED PREVIOUSLY, I WOULD LIKE TO SUGGEST CZOCHRALSKI AS AN ALTERNATIVE TO CASTING. LARGE DIAMETER INGOTS (IN THE 12" RANGE) HAVE BEEN GROWN IN THE KAYEX TECHNOLOGY CENTER AT A RATE OF 6 KG/HR. CERTAINLY, SEVERAL OF THESE INGOTS COULD BE PRODUCED FROM THE SAME CRUCIBLE. THERMAL SHOCK CRACKING AND CRUCIBLE OR MOLD PROBLEMS WOULD BE ELIMINATED. THE INGOTS WOULD BE CROPPED, SECTIONED AND SLICED JUST LIKE CAST INGOTS.

YOU MAY ASK, "WHY DOESN'T INDUSTRY GO AHEAD AND INVEST DOLLARS IN THESE IDEAS IF THEY ARE SO GOOD?"

SMALL EQUIPMENT MANUFACTURERS LIKE KAYEX ARE DRIVEN BY THE CUSTOMERS AND THE MARKETPLACE. 90% OF OUR PROJECTED CRYSTAL GROWER BUSINESS FOR THE FORESEEABLE FUTURE WILL COME FROM THE SEMICONDUCTOR INDUSTRY. OUR CORPORATE R AND D WILL BE DIRECTED TOWARD THAT MARKET - WE WILL BE CONCERNING OURSELVES AND OUR DESIGNS WITH, FOR EXAMPLE:

PLENARY SESSION: R.L. LANE

- OXYGEN CONTROL AND PRECIPITATION
- MICROSCOPIC AND MACROSCOPIC UNIFORMITY
- THERMAL GRADIENTS IN THE GROWING CRYSTAL AND IN THE MELT
- MAGNETIC CZ GROWTH
- AUTOMATION

TO THE EXTENT THESE DEVELOPMENT PROJECTS ARE USEFUL TO PHOTOVOLTAICS, WE WILL APPLY THEIR RESULTS; HOWEVER, IT WILL BE OF LIMITED USE.

IT TAKES 2-3 YEARS TO BRING A CONCEPT FROM THE LABORATORY TO THE MARKETPLACE. WE ARE SEEING SOME OF THE RESULTS OF OUR PREVIOUS WORK BEING USED NOW.

THE MOMENTUM OF DEVELOPMENT OF PHOTOVOLTAIC CZ MATERIALS AND EQUIPMENT MUST BE KEPT UP IF REAL COMMERCIAL PROGRESS IS TO BE MADE IN FUTURE YEARS.

BLOCK V MODULE DESIGN SUMMARY

JET PROPULSION LABORATORY

L.D. Runkle ✓

Objective

- **Design to Be Commercially Viable**
- **Advance in State of the Art Over Block IV**
- **Improved Reliability and Durability**
- **Consider System Implications**

Contract Requirements

- **Preliminary Design of Module**
 - **Electrical**
 - **Thermal**
 - **Mechanical**
- **Preliminary Inspection System Plan**
- **Documentation**

Schedule

- | | |
|-----------------------------|--------------------------------|
| • RFP Issued | Feb. 27, 1981 |
| • Proposals Received | April 10, 1981 |
| • Contracts Started | Aug. 7 - Sept. 25, 1981 |
| • Completions | Nov. 81 - Feb. 82 |

Module Characteristics

	Size (cm)		Mass (kg)	V _{no} (V)	NOCT °C	P(NOC) (W)	P _p (W)	Efficiency (%)	
	Length	Width						NOC	PEAK
ARCO	122	61	11	4.8	49	50	72	8.4	9.7
GE	123	63		14.3	61	58	90	9.2	11.5
MTSEC	168	120		17.5	47	126	176	7.8	8.8
RCA	122	118	22.6	5.3	42	86	114	7.6	8.0
Solarex	138	96	23.6	15.0	49	77	108	7.2	8.1
Spire	113	61	7.3	15.0	49	54	78	10.1	11.3

NOC 80 mW/cm², AM1.5, NOCTNOCT 80 mW/cm², 20°C Ambient, 1 m/sec WindPEAK 100 mW/cm², AM1.5, 25°C

Cell and Circuit Features

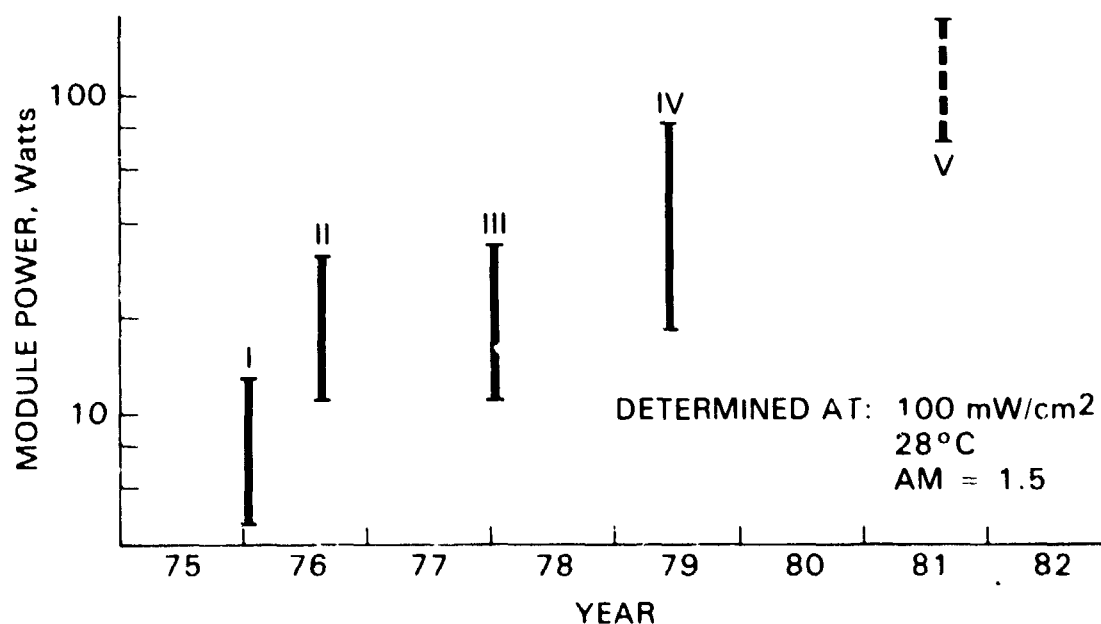
	Size (cm)	Base Material	Encapsulated Cell Efficiency		Total Cells	Series Cells	Parallel Cells	Series per Diode	Number of Diodes
			PEAK	NOC					
ARCO	10.3 (dia)	Cz	13.4	11.6	56	11	6	-	0
GE	10x10	Cz	12.9	10.4	72	36	2	12	3
MTSEC	5x10	EFG	9.8	8.8	352	44	8	11	4
RCA	10 (dia) w/flats	Cz	10.2	9.6	144	12	12	-	0
Solarex	10x15	Semi Crystal	9.2	8.2	78	39	2	13	3
Spire	10 (dia) w/flats	Cz	14.4	12.6	72	36	2	12	3

NOC 80 mW/cm², AM1.5, NOCTNOC 80 mW/cm², 20°C Ambient, 1 m/sec WindPeak 100 mW/cm², AM1.5, 25°C

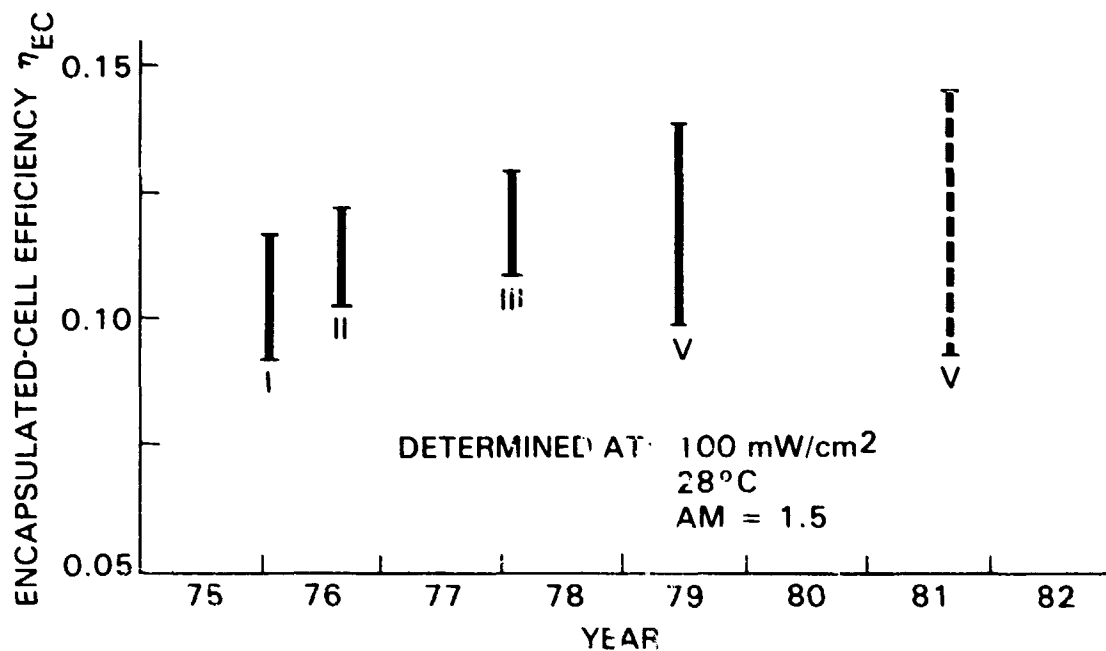
Encapsulation Features

	Top Cover or Superstrate	Pot- tant	Spacer	Back Cover or Substrate (From inside out)	Frame
ARCO	3.18-mm Tempered Water-white glass	EVA	None	Ted-Poly-Al-Ted	Anodized Al
GE	5-mm Tempered Sunadex Glass	EVA	Scrim	Ted-Poly-Al-Ted	None (Shingle)
MTSEC	5-mm Tempered Water-white Glass	EVA	-	Poly-Al-Ted	None
RCA	3.18-mm Tempered Water-white Glass	EVA	Craneglas	3.18-mm Tempered Float Glass	EPDM Gasket
Solarex	3.18-mm Tempered Water-white Glass	EVA	Craneglas	Poly-Ted	Gasket
Spire	3.18-mm Tempered Heliolite or Solatex Glass	EVA	Glass Fiber	Tedlar	EPDM Gasket & Glide

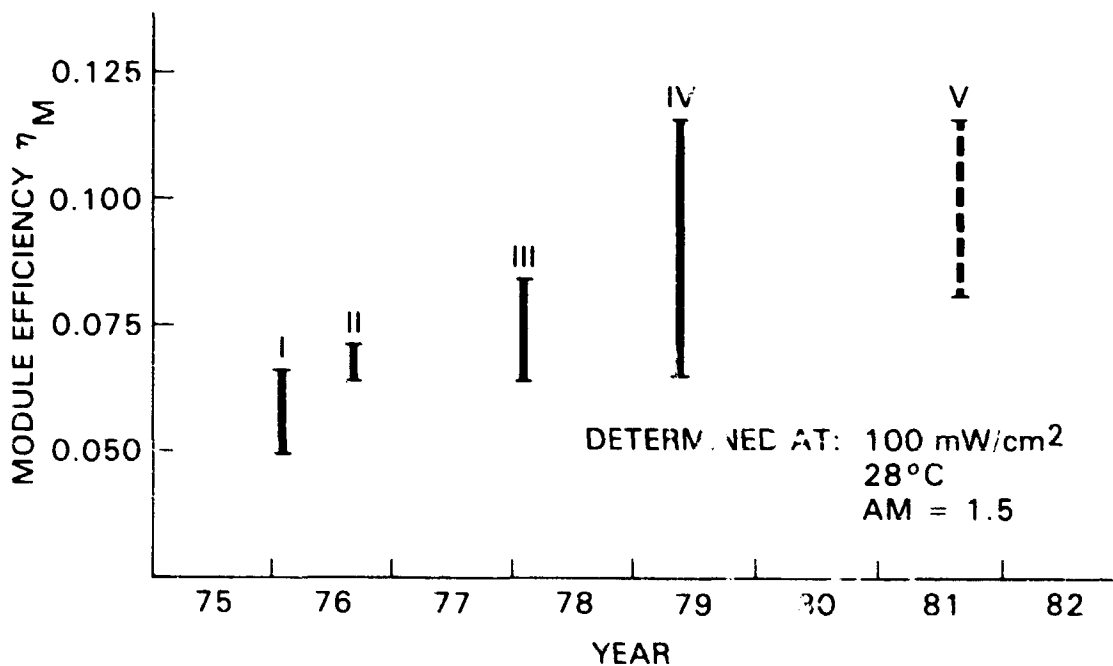
Module Power Trend



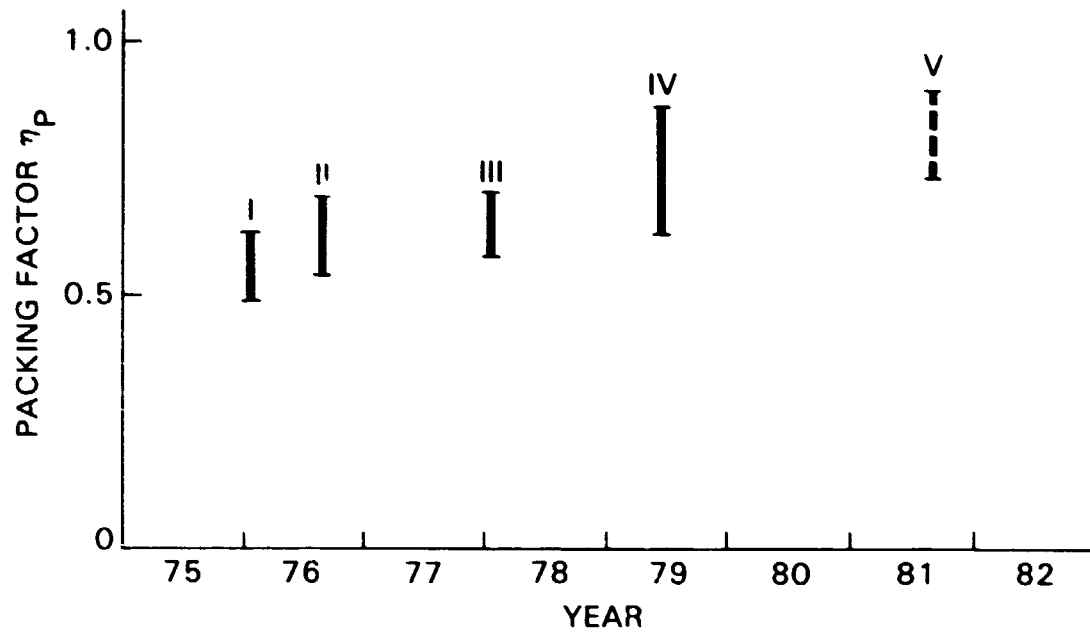
Cell Efficiency



Module Efficiency



Packing Factor



CENTRAL-STATION APPLICATIONS System and Subsystem Research Activities*

SANDIA NATIONAL LABORATORIES

G.J. Jones ✓

Photovoltaic central power stations were first analyzed in three parallel studies by General Electric Co., Spectrolab, Inc., and Westinghouse Electric Corp., published in 1977. A number of questions raised in these efforts have been the subject of more focused research over the last few years. This presentation reviews the work done in this area by Sandia National Laboratories as part of their system and balance-of-system research activities. The work has been broken into three topical areas starting with subsystems, proceeding to detailed design definition, and culminating in the analysis of the system's value to, and impact on, the utility.

Several flat-panel array field design studies, for both large intermediate and central-station applications, predict that \$50/m² area-related costs are achievable, by a number of concepts. This cost is based on vendor quotes and construction contractor bids. In the future, use of automation and robotics in structure placement and panel installation may be able to lower this cost by 20%. In the area of power conditioning, central-station-sized equipment has been developed for other technologies, but not yet for photovoltaics. Conceptual designs for such a unit will be sought in the near future.

Bechtel recently completed a study of electrical design tradeoffs for multimegawatt systems. They analyzed such factors as the subfield size versus voltage, energy loss, and power-conditioning and wiring cost. These results indicate that 5 MW subfield operating at 2000 Vdc bipolar (+ 1000 Vdc) is near optimum and does not adversely impact collector design. All of the results of this study, as well as the utility requirements identified in the test facility design studies, have been incorporated into the reference designs being developed by Martin Marietta. These designs are site-specific and utilize existing prototype hardware. There is active utility (APL) participation in this work and an experienced construction engineering firm (Stearns-Rogers) as subcontractor.

The analysis of central-station plant value and impact on the utility is a relatively new activity. The value of PV central station plants as a function of region can be determined from the energy scenario effects study, recently completed by General Electric. This work focused on distributed PV applications but the value analysis is equally applicable to central stations. Regions with high oil and gas use were found to offer high value, as would be expected. The analysis of the impact of PV systems on the utility's spinning reserve requirements will be studied by Arizona State University. This work will be directed by Paul Anderson and will involve utility consultants on generation planning, dispatch, and distribution.

*This work was supported by the U.S. Department of Energy, Division of Photovoltaic Technology

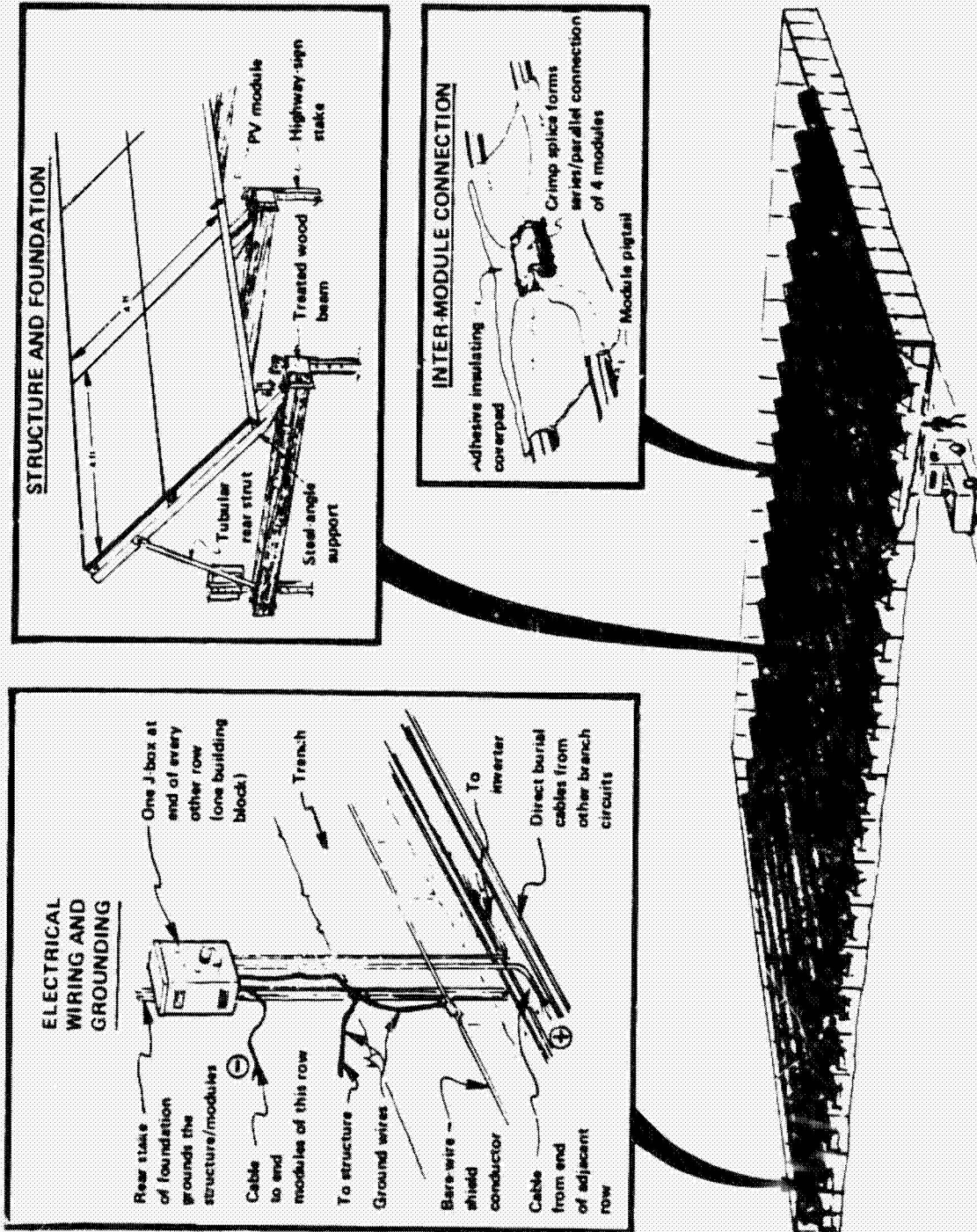
PLENARY SESSION: G.J. JONES

AREAS OF RESEARCH:

- ARRAY FIELD ENGINEERING AND POWER CONDITIONING DEVELOPMENT
- DESIGN TRADEOFF ANALYSIS AND DETAILED DESIGN PREPARATION
- UTILITY VALUE AND OPERATIONAL IMPACTS DETERMINATION

Array Field Engineering

- MODULAR ARRAY FIELD DESIGNS
(20-500 kW SUBFIELD)
 - BATTELLE-COLUMBUS (SAND81-7183)
 - HUGHES (SAND81-7193)
- INTEGRATED ARRAY/STRUCTURE DESIGN
 - BECHTEL (SAND81-7191)
- AUTOMATED INSTALLATION TECHNIQUES
 - BURT HILL KOSAR RITTLEMAN (SAND81-7192)



PHOTOVOLTAIC ARRAY FIELD USING BATTELLE'S LOW-COST BUILDING BLOCK DESIGN
100-kW Array field consists of 10 building blocks, 2 rows each. Size to fence is ~185 x 195 ft.

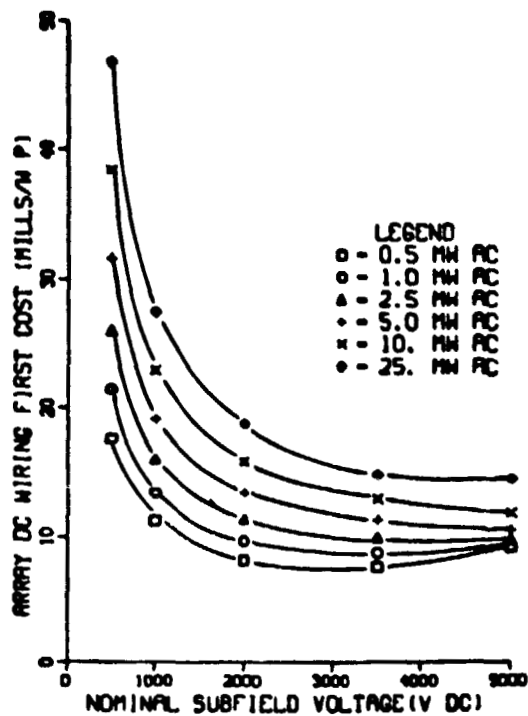
Array Field Design Summary

- CONSTRUCTION CONTRACTOR COSTING OF ARRAY FIELD DESIGNS PREDICT AREA-RELATED BOS COSTS OF \$50/M², (SITE PREP., STRUCTURE, INSTALLATION, WIRING, ETC.)
- AN APPROPRIATE MIX OF AUTOMATED AND CONVENTIONAL INSTALLATION METHODS MAY REDUCE COSTS BY ABOUT \$11/M².

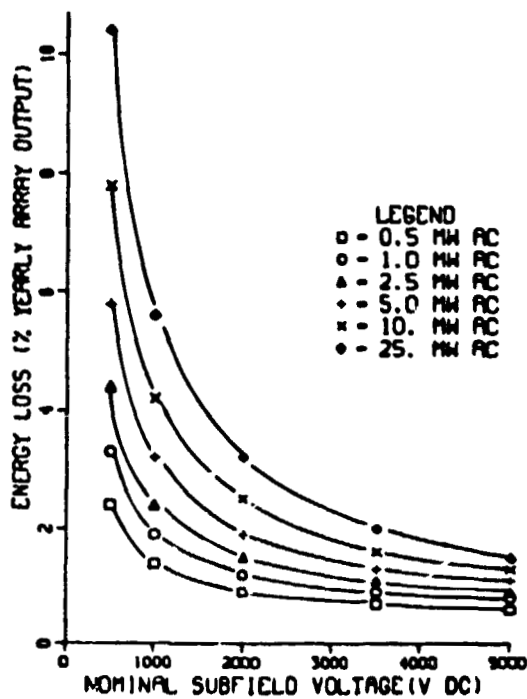
Design Tradeoffs and Detailed Preparation

- CENTRAL POWER STATION TEST FACILITY DESIGN
 - BECHTEL (SAND79-7012)
 - GENERAL ELECTRIC (SAND79-7022)
- SUBSYSTEM OPTIMIZATION AND DESIGN TRADEOFF STUDY
 - BECHTEL (SAND81-7013)
- CENTRAL STATION REFERENCE DESIGN
 - MARTIN MARIETTA (IN PROGRESS)

PLENARY SESSION: G.J. JONES



(a) FIRST COSTS



(b) ENERGY LOSSES

Vertical Axis Array Dc Wiring First Costs and I^2R Energy Losses - 25 Meter Diameter,
15 Percent Efficiency

Central-Station Reference Design (Martin-Marietta)

- SITE SPECIFIC DESIGN USING ACTUAL SOIL AND TERRAIN CHARACTERISTICS
 - SAGUARO POWER STATION, APS
- TWO COMPLETE 100 MW FIELD DESIGNS
 - FLAT PLATE: DENDRITIC WEB MODULES AND BECHTEL INTEGRATED STRUCTURE DESIGN
 - CONCENTRATOR: MARTIN-MARIETTA MOD 2 POINT FOCUS FRESNEL
- FIELD CHARACTERISTICS BASED ON SUBSYSTEM OPTIMIZATION STUDY
 - 5 MW (AC) SUBFIELD
 - 2000 V BIPOLAR DC WIRING
 - 34,5 kV INFIELDC AC DISTRIBUTION

Design Information Summary

- SEVERAL TECHNIQUES HAVE BEEN FOUND TO REDUCE IN-FIELD DC WIRING
- ALMOST ALL ECONOMIES OF SCALE AND ENERGY LOSS MINIMIZATION CAN BE ACHIEVED BY 5 MW, \pm 1000 VDC SUBFIELD
- DESIGN TRADEOFFS MUST CONSIDER LIFE CYCLE VALUE OF ENERGY LOSS IN CONJUNCTION WITH FIRST COST TO DETERMINE OPTIMUM.

Utility Value/Impact Determination

- THE EFFECT OF FUTURE ENERGY SCENARIOS ON PHOTOVOLTAIC ENERGY VALUE
 - GENERAL ELECTRIC (SAND81-7012)
- THE IMPACT OF STOCHASTIC PV ENERGY SUPPLY ON UTILITY OPERATIONS
 - ARIZONA STATE UNIVERSITY (IN PROGRESS)

Utility Value Determination

- REGIONS WITH HIGH OIL AND GAS USAGE IN INTERMEDIATE AND BASE LOAD GENERATION ARE FAVORED.
- ONLY FUTURE SCENARIOS AFFECTING OIL/GAS USE AND VALUE AFFECT PV ENERGY VALUE IN THESE REGIONS.
- DISTRIBUTED AND CENTRALIZED PV PLANTS HAVE THE SAME ENERGY VALUE TO THE GRID (ASSUMING NEGLIGIBLE T&D IMPACT).

PV LARGE SYSTEMS PROJECT

AEROSPACE CORP.

S. L. Leonard ✓

Utility Oil Conservation A Near-Term PV Central-Station Market

• PRIMARY MARKET AREAS

- CALIFORNIA, FLORIDA, HAWAII, PUERTO RICO
- OIL-DEPENDENT
- HIGH INSOLATION
- PRESENT (1978) OIL USE:
500,000 BBL/DAY (30% OF U.S.
UTILITY OIL CONSUMPTION)

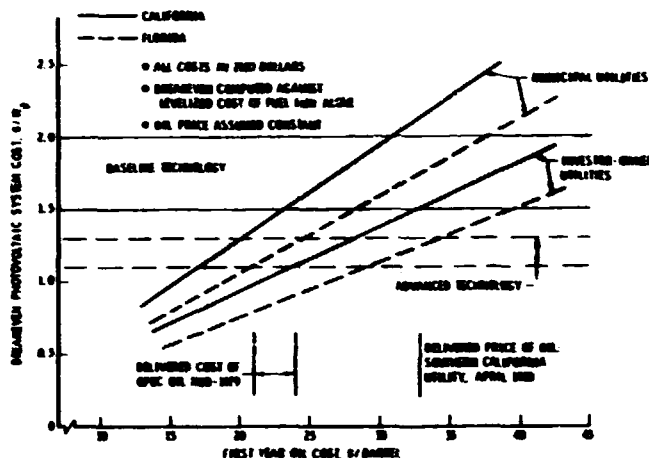
• SECONDARY MARKET AREAS

- LOUISIANA, TEXAS, OKLAHOMA
- DEPENDENT ON NATURAL GAS, OIL
- GOOD INSOLATION
- PRESENT (1978) OIL USE:
85,000 BBL/DAY
- PRESENT (1978) NATURAL GAS USE:
1,000,000 BBL/DAY (OIL
EQUIVALENT)

• CONCLUSION

- IF BASELINE TECHNOLOGY COMMERCIAL READINESS GOALS ARE REACHED, IT WILL BE COST-EFFECTIVE BY THE LATE 1980's IN THE PRIMARY MARKET AREAS TO CONSTRUCT PHOTOVOLTAIC PLANTS SOLELY TO REDUCE OIL CONSUMPTION, EVEN IF THE REAL (inflation-adjusted) PRICE OF OIL DOES NOT INCREASE OVER 1980 VALUES

BREAKEVEN PHOTOVOLTAIC SYSTEM COST vs
OIL-STEAM POWER GENERATION



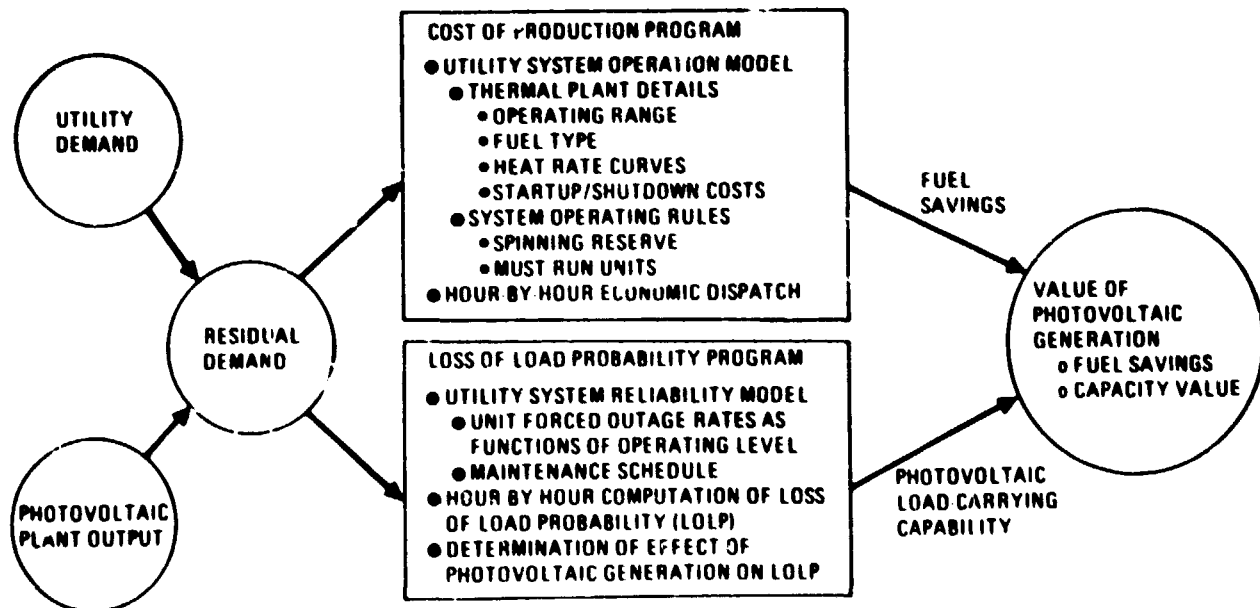
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Issues

- QUESTION: IS THIS APPARENT OPPORTUNITY REAL, OR IS THE ANALYTICAL APPROACH TOO SIMPLIFIED?
 - RESPONSE: DETAILED ANALYSES OF VALUE OF PHOTOVOLTAIC GENERATION IN SPECIFIC OIL-DEPENDENT SUNBELT UTILITIES
- QUESTION: ARE THESE RESULTS CREDIBLE TO THE INDUSTRIES THAT WOULD BE INVOLVED?
 - RESPONSE: EXTENSIVE IN-DEPTH DISCUSSIONS WITH REPRESENTATIVE ORGANIZATIONS IN THE UTILITY, PHOTOVOLTAIC MANUFACTURING, AND CONSTRUCTION INDUSTRIES
- QUESTION: HOW CAN TECHNICAL AND ECONOMIC RISKS BE REDUCED TO THE POINT THAT THE PRIVATE SECTOR WILL TAKE ADVANTAGE OF THIS OPPORTUNITY?
 - RESPONSE: ANALYSES OF INNOVATIVE FINANCING ARRANGEMENTS THAT COULD LEAD TO HAND-OFF TO THE PRIVATE SECTOR AT CURRENTLY ACHIEVABLE SYSTEM COSTS, ONCE TECHNICAL FEASIBILITY HAS BEEN DEMONSTRATED

SUPPORT OF FEDERAL PARTICIPATION IN INITIAL UTILITY-SCALE PROJECTS THAT DEMONSTRATE TECHNICAL FEASIBILITY OF LARGE PHOTOVOLTAIC SYSTEMS FOR UTILITY APPLICATIONS

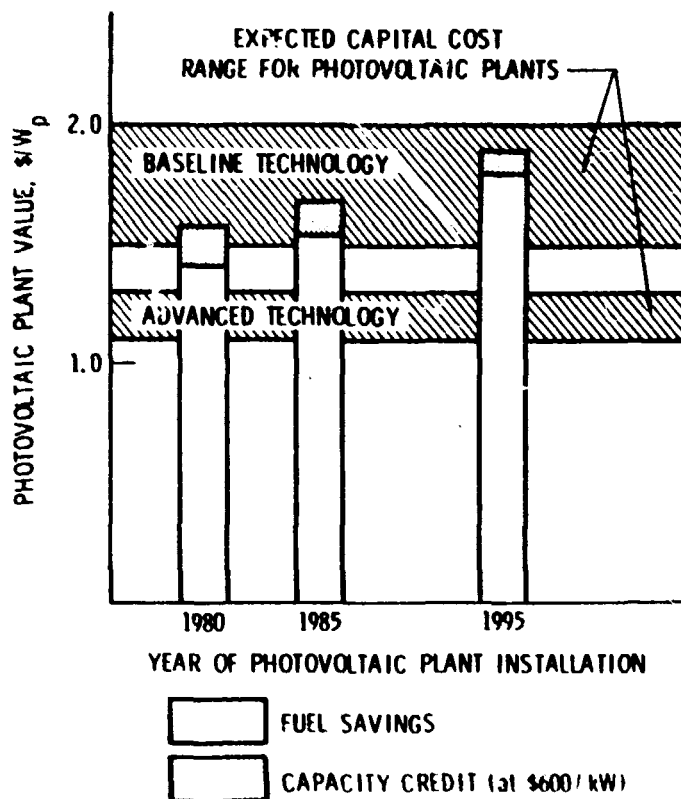
Value Analysis Methodology



Value of PV Power Plants in the Southern California Edison System

ASSUMPTIONS

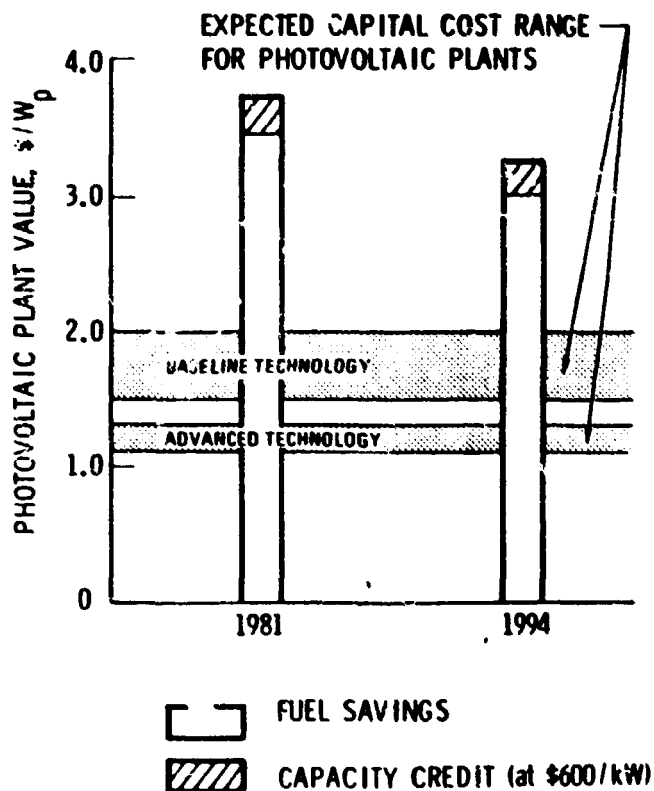
- ALL COSTS IN 1980 DOLLARS
- GENERAL INFLATION RATE
 - 1981 - 1987: ~ 8.4% / YR
 - 1988 - : 5% / YR
- REAL FUEL PRICE ESCALATION
 - 1981 - 1984: ~ 2.7% / YR
 - 1985 - : 2% / YR
- PHOTOVOLTAIC SYSTEM LIFE: 30 YR
- PHOTOVOLTAIC PENETRATION
 - ENERGY: 5%
 - CAPACITY: 11%



Value of PV Power Plants in the Los Angeles Department of Water and Power System

ASSUMPTIONS

- ALL COSTS IN 1981 DOLLARS
- GENERAL INFLATION RATE
 - 1981 - 85: 9.12% / YEAR
 - 1986 - 90: 8.30% / YEAR
 - 1991 - : 5.95% / YEAR
- REAL FUEL PRICE ESCALATION
 - 1981 - 85: 0.88% / YEAR
 - 1986 - 90: 1.70% / YEAR
 - 1991 - : 2.05% / YEAR
- PHOTOVOLTAIC SYSTEM LIFE: 30 YEARS
- PHOTOVOLTAIC PENETRATION
 - 1981: 2.1% OF ELECTRIC ENERGY FROM THERMAL UNITS
 - 1994: 1.5% OF ELECTRIC ENERGY FROM THERMAL UNITS



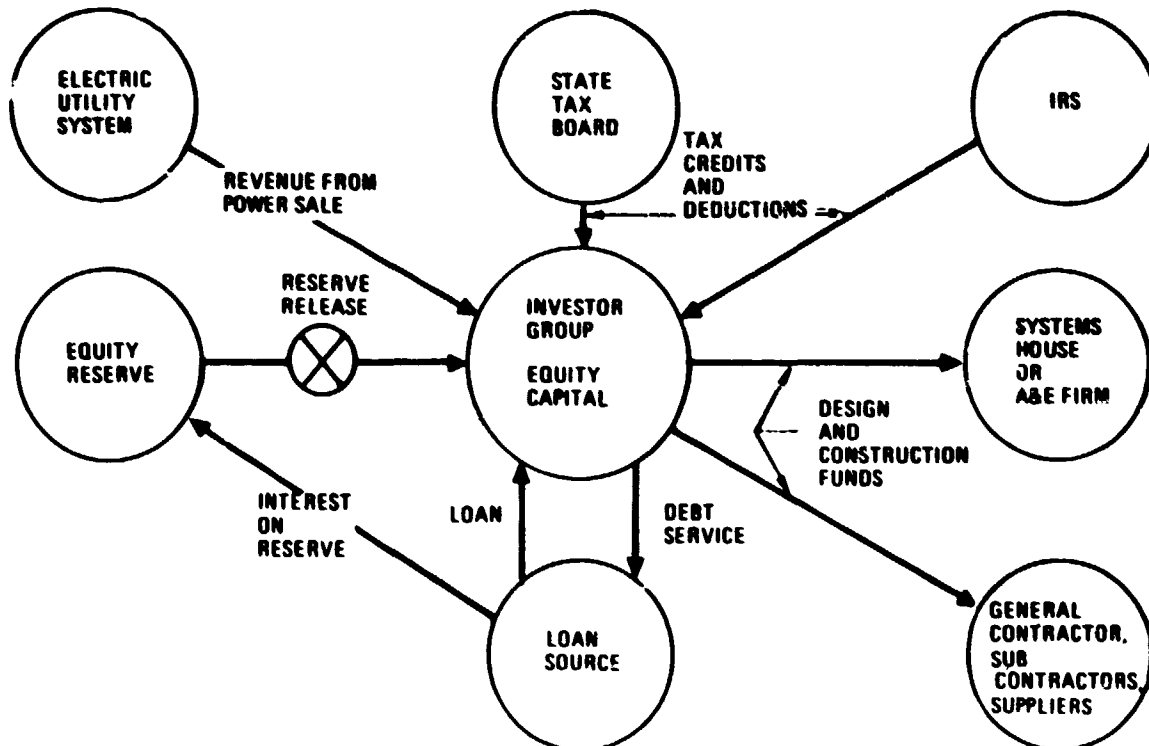
Third-Party Ownership Option

CONCEPT:

INVESTOR GROUP FINANCES CONSTRUCTION OF PHOTOVOLTAIC POWER PLANT, SELLS ELECTRICITY TO UTILITY, TAKES ADVANTAGE OF TAX INCENTIVES NOT AVAILABLE TO UTILITY

ADVANTAGE:

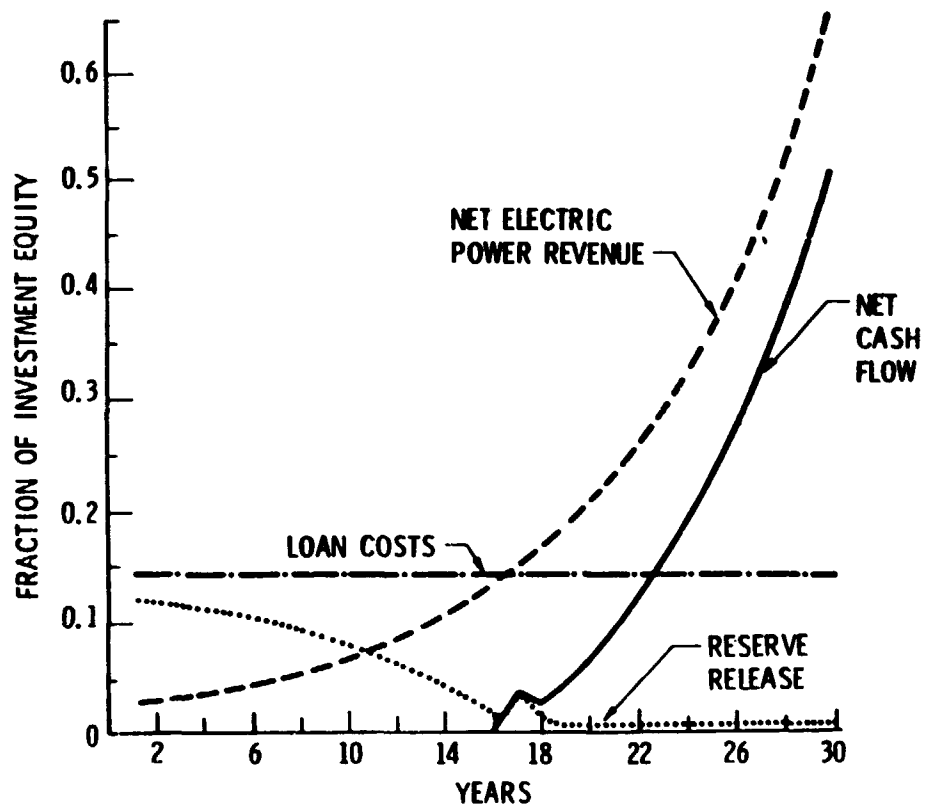
INCLUSION OF TAX BENEFITS MAKES INVESTMENT ATTRACTIVE WHEN COST OF PLANT IS STILL TOO HIGH FOR UTILITY PURCHASE



Investment Evaluation: Third-Party Financing Arrangement

ECONOMIC ASSUMPTIONS			
SYSTEM COST (\$/W _p)	13.00	10.50	7.00
REAL ESCALATION OF ELECTRICITY PRICE	5%/yr	3%/yr	0%/yr
EQUITY CAPITAL (% of system cost)	25	25	50
DEBT CAPITAL (% of system cost)	75	75	50
EQUITY RESERVE (% of system cost)	50	48	21
REQUIRED AFTER-TAX RETURN ON EQUITY	15%/yr	15%/yr	15%/yr
BENEFIT/COST BREAKDOWN (After-Tax Net Present Value as Percentage of Equity)			
FEDERAL INVESTMENT TAX CREDIT	12.4	12.8	13.0
FEDERAL ENERGY CREDIT	18.7	19.2	19.6
CALIFORNIA ENERGY CREDIT (net of Federal Tax)	16.8	17.2	17.6
DEPRECIATION: FEDERAL	37.9	38.9	39.8
CALIFORNIA (net of Federal Tax)	4.3	4.4	4.5
NET LOAN COST (less interest shelter)	(46.8)	(48.1)	(32.7)
NET ELECTRIC POWER REVENUE (net of O&M)	15.5	15.6	17.4
RESERVE RELEASE	21.8	22.1	12.7
RESERVE INTEREST	19.4	18.9	7.6
	100.0	101.0	99.5

Before-Tax Cash Flow



Investment Evaluation: Selected Sensitivities

ECONOMIC ASSUMPTIONS				
SYSTEM COST (\$/W _p)	10.50	6.00	7.60	4.50
SYSTEM SERVICE LIFE (years)	30	20	30	30
REAL ESCALATION OF ELECTRICITY PRICE	3%/yr	3%/yr	3%/yr	3%/yr
EQUITY CAPITAL (percent of system cost)	25	60	25	30
DEBT CAPITAL (percent of system cost)	75	40	75	70
EQUITY RESERVE (percent of system cost)	47.4	9.65	50	21.2
RATE OF INTEREST ON DEBT	12%	12%	16%	12%
REQUIRED AFTER-TAX RETURN ON EQUITY	15%	15%	15%	15%
FEDERAL AND STATE SOLAR TAX CREDITS	YES	YES	YES	NO
BENEFIT/COST BREAKDOWN (after-tax net present value as percentage of equity)				
FEDERAL INVESTMENT TAX CREDIT	12.8	13.4	12.4	18.2
FEDERAL ENERGY CREDIT	19.2	20.1	18.7	0
CALIFORNIA ENERGY CREDIT (net of federal tax)	17.2	18.1	16.8	0
DEPRECIATION: FEDERAL	38.9	40.8	37.9	55.5
CALIFORNIA (net of federal tax)	4.4	4.6	4.2	6.2
NET LOAN COST (less interest shelter)	(48.1)	(31.2)	(58.7)	(64.0)
NET ELECTRIC POWER REVENUE (net of O&M)	15.6	22.7	21.0	51.9
RESERVE RELEASE	22.1	9.2	23.5	24.9
RESERVE INTEREST	18.9	2.2	25.0	7.6
	101.0	99.9	100.8	100.3

Current Large-System Projects

- SACRAMENTO MUNICIPAL UTILITY DISTRICT PROJECT
 - PLANNED CAPACITY: 1 MW_p (AC)
 - SITE: RANCHO SECO NUCLEAR POWER PLANT, 30 MILES SOUTH OF SACRAMENTO, CALIFORNIA
 - FUNDING ALLOCATION: \$12 MILLION -- \$6.8 MILLION FROM DOE, \$2 MILLION FROM STATE OF CALIFORNIA, \$3.2 MILLION FROM SMUD
 - PROJECTED IOC DATE: JUNE 1984
 - FIRST STAGE OF PLANNED 100 MW_p PHOTOVOLTAIC POWER PLANT
- ARCO SOLAR / SOUTHERN CALIFORNIA EDISON COMPANY PROJECT
 - PLANNED CAPACITY: 1 MW_p (DC)
 - SITE: LUGO SUBSTATION NEAR VICTORVILLE, CALIFORNIA
 - ARCO SOLAR TO BE BUILDER, OWNER, AND OPERATOR
 - SOUTHERN CALIFORNIA EDISON TO PURCHASE AND DISTRIBUTE OUTPUT POWER
 - PROJECTED IOC DATE: DECEMBER 1982
 - PRIVATE VENTURE MADE POSSIBLE BY STATE AND FEDERAL TAX INCENTIVES

Conclusions

- DETAILED ANALYSES OF THE VALUE OF PHOTOVOLTAIC GENERATION TO SPECIFIC UTILITIES CONFIRM THE RESULTS OF SIMPLIFIED ANALYSIS
 - PHOTOVOLTAIC PLANTS COSTING \$1.50 - 2.00/W_p WOULD BE COST-EFFECTIVE IN AN OIL-DEPENDENT SOUTHWESTERN INVESTOR-OWNED UTILITY
 - THE BREAKEVEN COST IN A SIMILAR MUNICIPAL UTILITY WOULD BE EVEN LARGER: \$3.00 - 4.00/W_p
- THE PROGRESSIVE ELEMENTS OF THE UTILITY INDUSTRY ARE KEENLY INTERESTED IN PHOTOVOLTAIC TECHNOLOGY BUT REQUIRE ASSISTANCE TO PROCEED WITH LARGE COMMERCIAL (i.e., non-R&D) PROJECTS
 - RISKS ARISING FROM UNCERTAINTIES IN SYSTEM COST AND PERFORMANCE ARE TOO LARGE TO BE JUSTIFIED UNDER ALLOWED RATES OF RETURN
 - UTILITIES ARE, HOWEVER, WILLING TO ENTER INTO AGREEMENTS WITH THIRD-PARTY FINANCED PROJECTS
- UNDER A PROPERLY-STRUCTURED THIRD-PARTY ARRANGEMENT, CONSTRUCTING A PHOTOVOLTAIC PLANT AT CURRENTLY ACHIEVABLE COSTS CAN BE AN ATTRACTIVE INVESTMENT
 - CURRENT SOLAR TAX CREDITS CONTRIBUTE HEAVILY TO EFFECTIVE RATE OF RETURN ON INVESTMENT
 - LEVERAGED FINANCING AT REASONABLE RATES SIGNIFICANTLY INCREASES RETURNS

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SACRAMENTO MUNICIPAL UTILITY DISTRICT 100-MW_e PHOTOVOLTAIC POWER PLANT

JET PROPULSION LABORATORY

R.V. Powell ✓

Chronology

- **SMUD unsolicited proposal to:**
 - **U.S. Department of Energy (DOE)**
 - **California Energy Commission (CEC)**
- **Congress mandated \$6.8M for FY'82 for SMUD Project**
- **Negotiations for July 1982 start**

The SMUD Power-Plant Proposal

- **Unsolicited proposal (Dec. '81)**
- **100 MW in 10 phases - Rancho Seco site**
- **1 MW 1st phase - 24 months**
- **Design selected for 1st phase**
- **Alternative designs planned for later stages**
- **SMUD Project Manager**
- **CEC assist in environment impact**
- **Federal/State role is to share early cost risk**
- **Cooperative agreement**
- **Project Review Board**

PLENARY SESSION: R.V. POWELL

Special Features

- **Differential funding from government to limit cost/kW to a fixed value**
- **Government would be reimbursed when cost falls below fixed value**
- **Cost overruns would either be absorbed by SMUD or would result in a change of scope by the Project Review Board**

The Government Contract/Cooperative Agreement

- **DOE cooperative agreement, June '82**
- **CEC contract, June '82**
- **Limited to 1st 1 MW**
- **Alternative designs to be considered**
- **DOE/PV Design Assistance Team**
- **SMUD Project Manager**
- **Project Review Board**

OMIT

ENERGY ECONOMICS: DOES PHOTOVOLTAICS FIT IN?

SHELL OIL CO.

M. Sagenkehr

(Abridged)

1980 Energy Budget, Crude Oil Equivalents: MM bbl/day

	<u>TRANSP</u>	<u>RES./ COM'L</u>	<u>INDUST</u>	<u>CHEM FDSTKS</u>	<u>EXPORTS</u>	<u>ELEC UTIL</u>	<u>SYN CRUDE</u>	<u>SYN GAS</u>	<u>TOTAL</u>
OIL	8.5	2.4	2.9	1.0	0.5	1.4	-	-	16.7
GAS		3.7	4.0	0.3	-	1.8	-	-	9.8
COAL		0.1	1.6	-	1.1	5.8	-	-	8.6
NUCLEAR						1.2			1.2
HYDRO						1.4			1.4
SHALE							-		-
RENEWABLE						-			-
DELV'D ELECTRICITY	—	<u>2.1</u>	<u>1.3</u>	—	—	(3.4)	—	—	—
TOTALS	8.5	8.3	9.8	1.3	1.6	8.2	-	-	37.7

**Energy Growth in the United States, Crude Oil
Equivalents: MM bbl/day**

	1975		1980		1991		2000	
		<u>%</u>		<u>%</u>		<u>%</u>		<u>%</u>
OIL	15.5	46	16.7	44	16.2	38	14.1	30
GAS	9.5	28	9.8	26	7.5	18	6.8	14
COAL	6.9	20	8.6	23	12.8	30	19.7	41
NUCLEAR	.8	2	1.2	3	3.4	8	3.8	8
HYDRO	1.5	4	1.4	4	1.7	4	1.7	3
SHALE	-	-	-	-	0.5	1	1.0	2
RENEWABLE	-	-	-	-	0.4	1	0.9	2
TOTALS	34.2	100	37.7	100	42.5	100	48.0	100

2.0% AAI* 1.1% AAI 1.4% AAI

*ANNUALIZED AVERAGE INCREASE

**U.S. Electric Utility Input Energy by Full Source,
Crude Oil Equivalents: MM bbl/day**

	1975		1980		1991		2000	
		<u>%</u>		<u>%</u>		<u>%</u>		<u>%</u>
OIL	1.5	16	1.4	12	0.9	6	0.8	4
GAS	1.6	17	1.8	16	1.3	9	0.9	5
COAL	4.1	43	5.8	50	7.9	52	11.4	61
NUCLEAR	0.8	8	1.2	10	3.4	22	3.8	20
HYDRO	1.5	16	1.4	12	1.7	11	1.7	9
RENEWABLE	-	-	-	-	0.1	-	0.2	1
DELV'D ELEC.	(2.8)		(3.4)		(4.6)		(5.8)	
TOTALS	6.7		8.2		10.7		13.0	
ENERGY INPUT								

4.0% AAI 2.8% AAI 2.6% AAI

PLENARY SESSION: M. SAGENKAHN

Solar Energy Forecast (Consistent With Total Energy Forecast)

- o OF 0.9 MM BBL/DAY COE RENEWABLE ENERGY FORECAST TO 2000, 0.2 MM BBL/DAY WOULD BE SOLAR
- o OF 0.2 MM BBL/DAY SOLAR, 20% WOULD BE PHOTOVOLTAIC
- o THE 0.4 MM BBL/DAY PHOTOVOLTAIC WOULD BE DIVIDED ABOUT EQUALLY BETWEEN RESIDENTIAL/COMMERCIAL, INDUSTRIAL AND ELECTRIC UTILITY

1991 Energy Budget, Crude Oil Equivalents: MM bbl/day

	<u>TRANSP</u>	<u>RES./</u> <u>COM'L</u>	<u>INDUST</u>	<u>CHEM</u> <u>FDSTKS</u>	<u>EXPORTS</u>	<u>ELEC</u> <u>UTIL</u>	<u>SYN</u> <u>CRUDE</u>	<u>SYN</u> <u>GAS</u>	<u>TOTAL</u>
OIL	9.5	2.1	2.9	1.3	0.3	0.9	(0.9)	0.1	16.2
GAS		3.8	2.7	0.3	-	1.3	-	(0.6)	9.8
COAL		0.1	2.1	-	1.5	7.9	0.6	0.6	12.8
NUCLEAR						3.4			3.4
HYDRO						1.7			1.7
SHALE							0.5		0.5
RENEWABLE		0.1	0.2			0.1			0.4
DELV'D ELECTRICITY	—	<u>2.8</u>	<u>1.8</u>	—	—	(4.6)	—	—	—
TOTALS	9.5	8.9	9.7	1.6	1.8	10.7	0.2	0.1	42.5

PLENARY SESSION: M. SAGENKAHN

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OF POOR QUALITY

2000 Energy Budget, Crude Oil Equivalents: MM bbl/day

	<u>TRANSP</u>	<u>RES./</u> <u>COM'L</u>	<u>INDUST</u>	<u>CHEM</u> <u>FDSTKS</u>	<u>EXPORTS</u>	<u>ELEC</u> <u>UTIL</u>	<u>SYN</u> <u>CRUDE</u>	<u>SYN</u> <u>GAS</u>	<u>TOTAL</u>
OIL	9.4	1.7	2.8	1.5	0.3	0.8	(2.4)		14.1
GAS		4.8	1.9	0.5	-	0.9		(1.3)	6.8
COAL			2.5		1.7	11.4	2.5	1.6	19.7
NUCLEAR						3.8			3.8
HYDRO						1.7			1.7
SHALE							1.0		1.0
RENEWABLE		0.2	0.5			0.2			0.9
DELV'D ELECTRICITY	—	<u>3.7</u>	<u>2.1</u>	—	—	<u>(5.8)</u>	—	—	—
TOTALS	9.4	10.4	9.8	2.0	2.0	13.0	1.1	0.3	48.0

Recent Energy Price Trends (Dec. 1980 to Sept. 1981)

	<u>% AAI</u>
PURCHASED INDUSTRIAL ELECTRICITY	21.5
CRUDE OIL (AV. REFINERS ACQUISITION COST)	9.0
NATURAL GAS (UTILITY COST)	46.0
COAL (UTILITY COST)	21.5

10 kW Diesel Generator

PREMISES

TOTAL INVESTMENT: \$37M TODAY
\$32M IN 15 YEARS
(EXPERIENCE CURVE EFFECT)

OPERATION & MAINTENANCE COSTS:
\$5000/YR NOW
\$4000/YR IN 15 YEARS

DIESEL PRICE: \$1.00/GALLON AT REFINERY GATE
\$0.40/GALLON DELIVERY

	<u>NOW</u>	<u>15 YEARS HENCE</u>		
		<u>3%*</u>	<u>1%*</u>	<u>-1%*</u>
REFINERY GATE	\$1.00	\$1.56	\$1.16	\$.84
DELIVERY	.40	.35	.35	.35
DELIVERED DIESEL				
PRICE	<u>\$1.40/GAL</u>	<u>\$1.91/GAL</u>	<u>\$1.51/GAL</u>	<u>\$1.91/GAL</u>

DOES NOT INCLUDE ANY BATTERY STORAGE

*REAL CRUDE OIL RATE OF INCREASE

10 kW Photovoltaic System

PREMISES

TOTAL INVESTMENT: FOR \$11/WP - \$700M
\$2.50/WP - \$275M

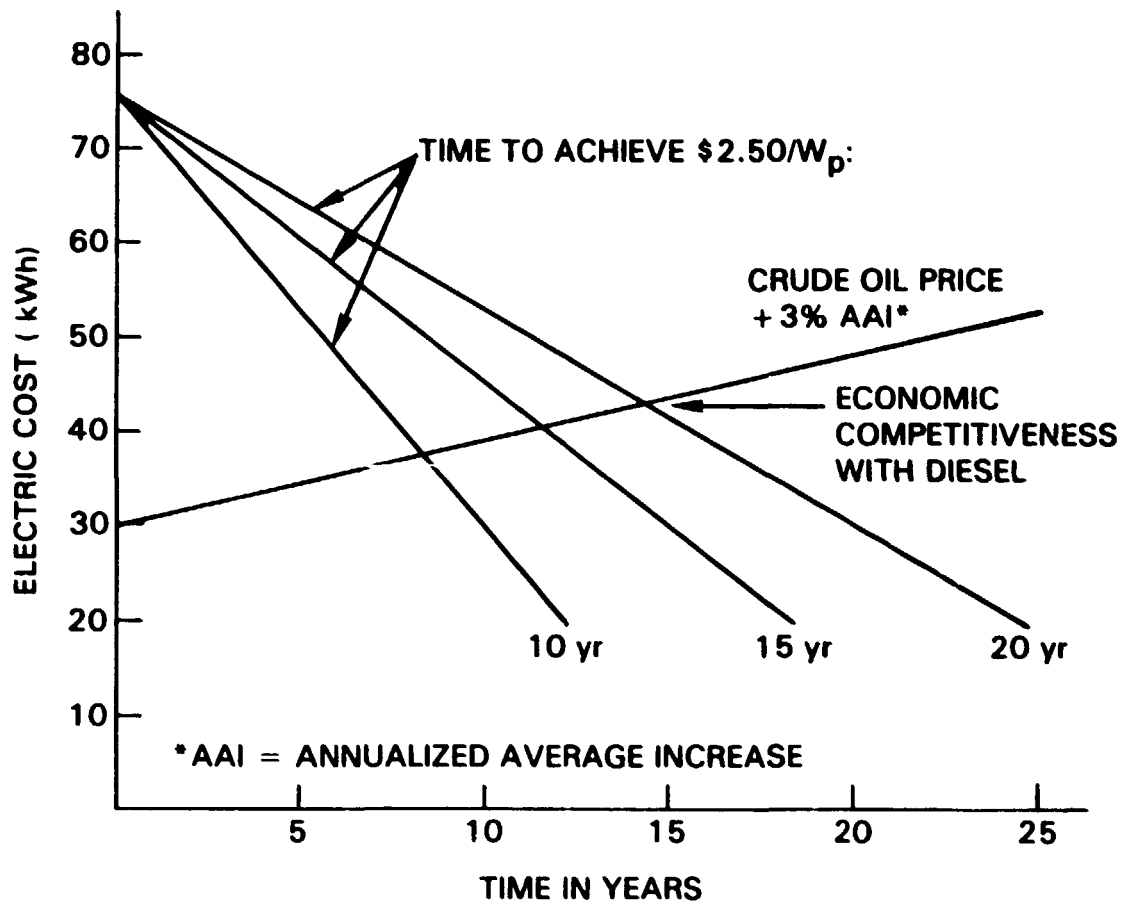
OPERATION & MAINTENANCE COSTS:
FOR \$11/WP - \$3000/YR
\$2.50/WP - \$2000/YR

LIFE OF SYSTEM - 20 YEARS

RETURN ON CAPITAL - 4% REAL

INCLUDES 1 DAY BATTERY STORAGE AT AN 80%
DEPTH OF DISCHARGE

Economic Comparison Between PV and Diesel-Generated Electricity for a 10 kW System



Conclusions

- o THE EXTREMELY RAPID INCREASE IN ENERGY COSTS DURING THE PAST DECADE HAS:
 1. CAUSED DRAMATIC REDUCTIONS IN DEMAND
 2. IMPROVED SUPPLY AND THE SUPPLY OUTLOOK
- o THE OUTLOOK FOR A COMFORTABLE U.S. ENERGY BALANCE TO THE END OF THIS CENTURY HAS BRIGHTENED CONSIDERABLY.
- o THE PRESSURE FOR DEVELOPMENT OF RENEWABLE SOURCES OF ENERGY AND COAL CONVERSION PROCESSES HAS, AS A RESULT OF THE ABOVE, LESSENERD.
- o THESE DEVELOPMENTS WILL, OF COURSE, STILL BE NEEDED TO FILL SUBSTANTIAL PORTIONS OF THE FUTURE ENERGY DEMAND. THE CURRENT SITUATION SUGGESTS THIS TIMING TO BE WELL INTO THE NEXT CENTURY.
- o THE EVENTUAL ECONOMIC COMPETITIVENESS OF PHOTOVOLTAICS FOR ANY GIVEN END USE IS, IN ANY EVENT, MORE A FUNCTION OF MANUFACTURING COST PER PEAK WATT OUTPUT THAN THE RATE OF REAL PRICE INCREASES OF TRADITIONAL ENERGY SOURCES.

PV HISTORY: LESSONS FOR THE FUTURE

SPECTROLAB, INC.

E.L. Ralph

PV Program Characteristics

- CREDIBILITY AT HIGH LEVEL
- PRACTICALITY HAS BEEN EMPHASIZED.
- LARGE SCALE APPLICATION PROVEN FEASIBLE
- LARGE TECHNOLOGY BASE (INDUSTRY, UNIVERSITY, GOVERNMENT)
- TERRESTRIAL INDUSTRY ESTABLISHED
- PRIDE IN BEING PART OF IT

Early Planning and Goals

- CONVENTIONAL SILICON TECHNOLOGY ~ \$2/W_p (1975 \$)
- ADVANCED SILICON TECHNOLOGY ~ \$0.50/W_p "
- FUTURE POTENTIAL ~ \$0.30/W_p "
- MARKETS CHANGE AS PRICES DECREASE
 REMOTE → LDC VILLAGES → RESIDENTIAL → POWER STATIONS
- INDUSTRY MUST BE WELL ESTABLISHED

PV Program History

- **BASED ON STRONG SPACE TECHNOLOGY (60's)**
- **STRUGGLING SOLAR ENERGY SOCIETY PROVIDED BACKGROUND**
- **"A PLAN" PRESENTED TO IEEE/PSC (1970)**
- **NSF/RANN PROGRAM SET GOALS (1971)**
- **NSF/FEA PROJECT INDEPENDENCE BLUEPRINT REPORT (1974)**
- **ERDA 10 YEAR PLAN INITIATED (1976)**

Major Accomplishments

- **FIRM PV REMOTE MARKET ESTABLISHED**
- **\$10/W_p MODULE IN PRODUCTION**
- **\$2.80/W_p MODULE TECHNOLOGY READY**
- **DICHLOROSILANE SILICON PROCESS DEVELOPED AND BEING APPLIED**
COSTS REDUCED FACTOR OF 3 AND CAPACITY DOUBLED
- **LARGE CZ CRYSTAL GROWTH FURNACES AVAILABLE**
MELT REPLENISHMENT, AUTOMATION, 4-6 INCH DIA.
- **SEVERAL SILICON SHEET TECHNOLOGIES DEMONSTRATED**
- **MODULE DURABILITY IMPROVED - FIELD TEST DATA AVAILABLE**
- **SYSTEM STUDIES INDICATE PHOTOVOLTAICS CAN COMPETE**
- **ALSO PROVIDED SIGNIFICANT BENEFITS TO OVERALL SEMICONDUCTOR INDUSTRY**

PLENARY SESSION: E.L. RALPH

Lessons for the Future

- THE TASK AHEAD IS LARGE (HIGH VOLUME LOW COST)
- TIME SCALE LONGER THAN PREDICTED (> 15 YEARS)
BUDGET CONSTRAINTS, CAPITAL INVESTMENT, MARKET GROWTH, OIL GLUT
- PLANS MUST BE MODIFIED AND BECOME MORE SELECTIVE
- OLD PROJECTIONS AND GOALS MUST BE REEVALUATED
- MAINTAIN CREDIBILITY AND RELEVANCE (BE PRACTICAL)
- RESEARCH ORIENTATION PROBABLY APPROPRIATE
ACCELERATED PROGRAM WOULD BE WASTEFUL

Research Objectives

- INCREASE EFFICIENCY
- LOWER MATERIAL COST
- AVOID DUPLICATION (GOVERNMENT AND INDUSTRY)
- EMPHASIZE HIGH RISK/HIGH PAYOFF

Research Needs

- MAJOR ADVANCEMENTS FROM CURRENT TECHNOLOGIES
(20-25% EFFICIENCY SINGLE OR SEMI-CRYSTAL SI OR GAAs)
 - MODELLING AND DEVICE DESIGN (INC. EFF.)
 - MATERIAL STUDIES
 - DEVICE/MODULE PROCESSES
 - ANALYTICAL METHODS
 - RELIABILITY PHYSICS
- ADVANCEMENTS FROM "NEXT STEP" TECHNOLOGIES
(12-17% EFFICIENCY THIN FILM POLYCRYSTALLINE MATERIALS)
 - MATERIAL STUDIES Si, CdTe, ZnP, GAAs, InP, CuInSe₂
 - EFFICIENCY IMPROVEMENT
 - CRYSTAL BOUNDARY EFFECTS
 - STABILITY PHYSICS
- ADVANCEMENTS FROM "LARGE STEP" TECHNOLOGIES
(25-50% EFFICIENCY ADVANCED CONCEPT CELL DESIGNS)
 - MULTI-BANDGAP APPROACHES
 - SUPERLATTICE STRUCTURES

UTILITIES PERSPECTIVE

OMIT

ELECTRIC POWER RESEARCH INSTITUTE

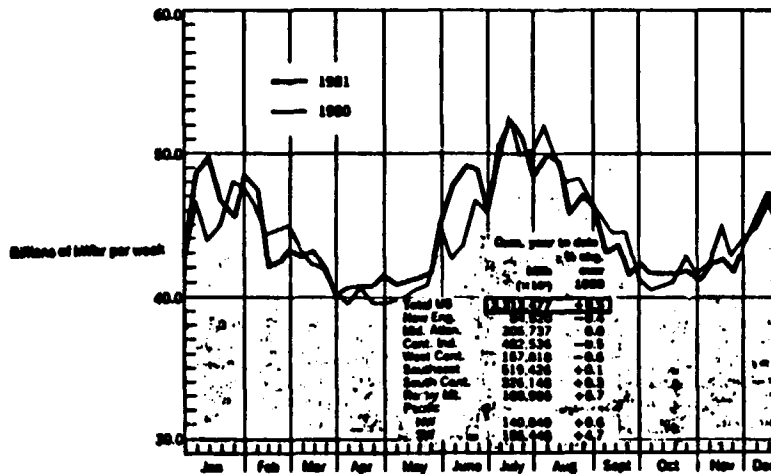
R.W. Taylor

"WOULD YOU TELL ME, PLEASE, WHICH WAY
I OUGHT TO GO FROM HERE?"

"THAT DEPENDS A GOOD DEAL ON WHERE
YOU WANT TO GET TO."

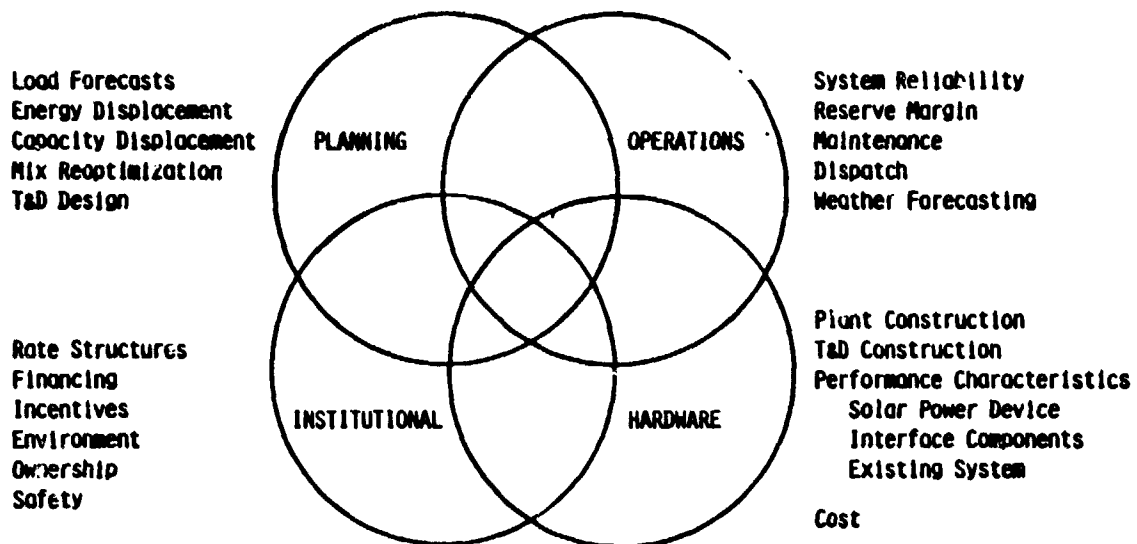
LEWIS CARROLL

Weekly U.S. Electric Consumption

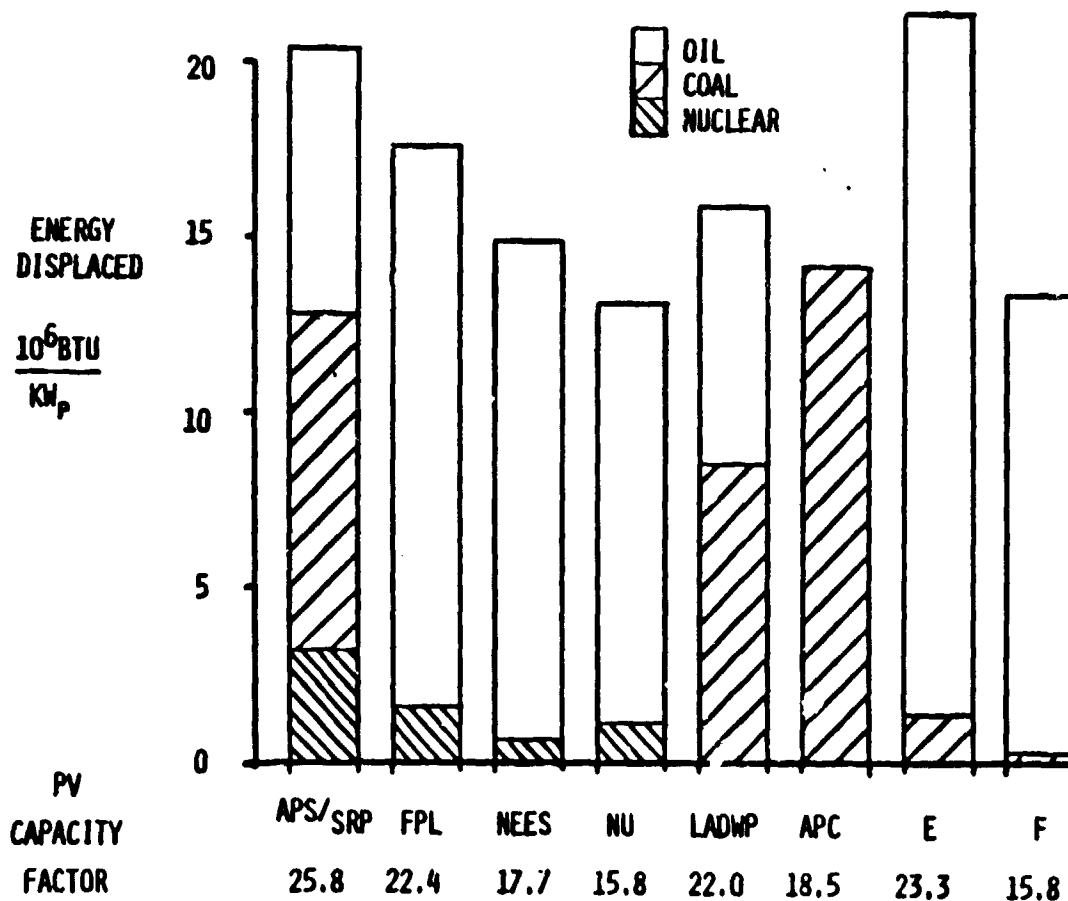


Statistical World, January 1982

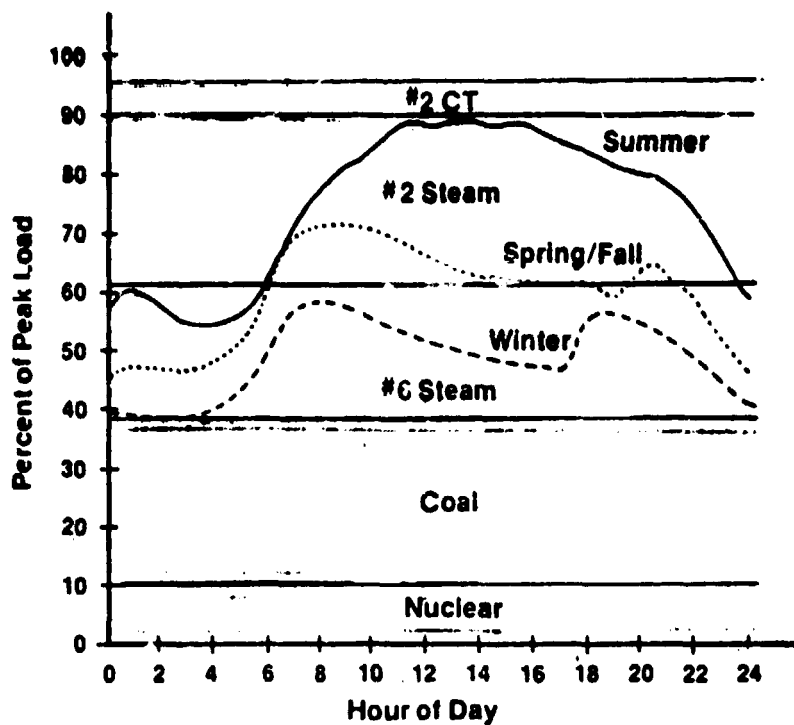
The Solar Equation



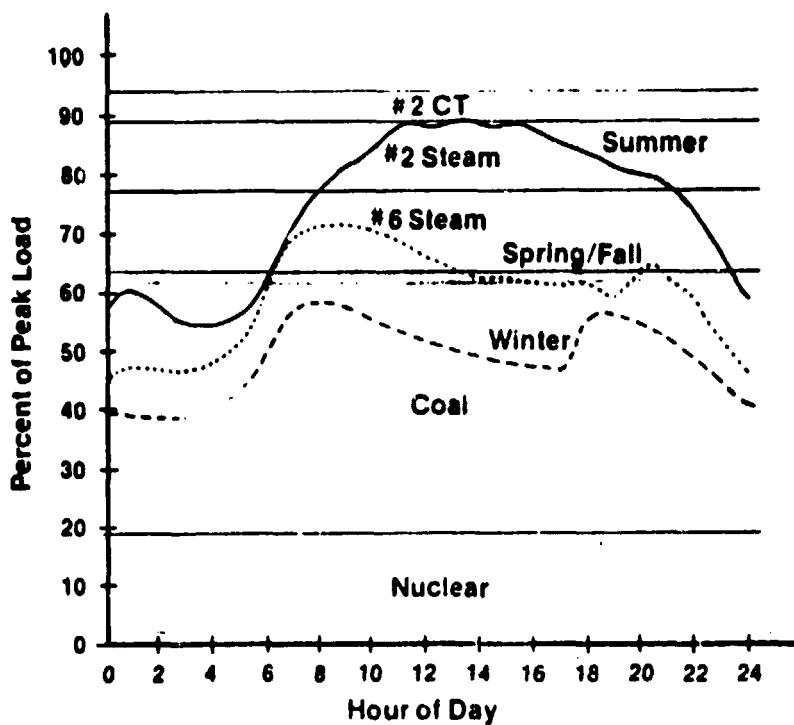
PV Value Analysis Comparison



1985 Load Profile and Fuel Mix: Reference Case

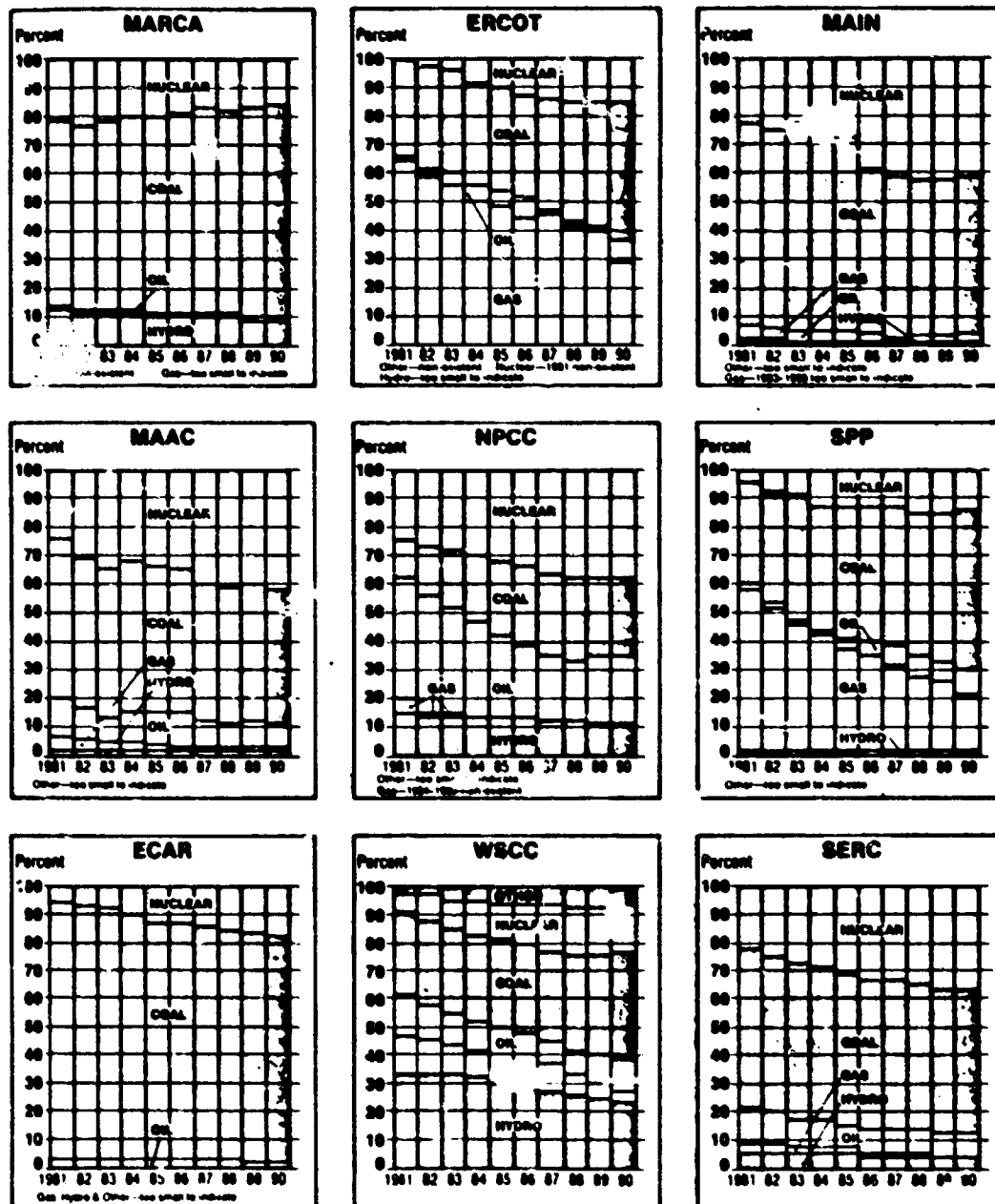


1998 Load Profile and Fuel Mix: Reference Case



Regional Electric Generation by Principal Energy Sources (by Percentage of Total)

(Contiguous U.S.)



FROM: Electric Power Supply and Demand 1981-1990
July 1981, National Electric Reliability Council

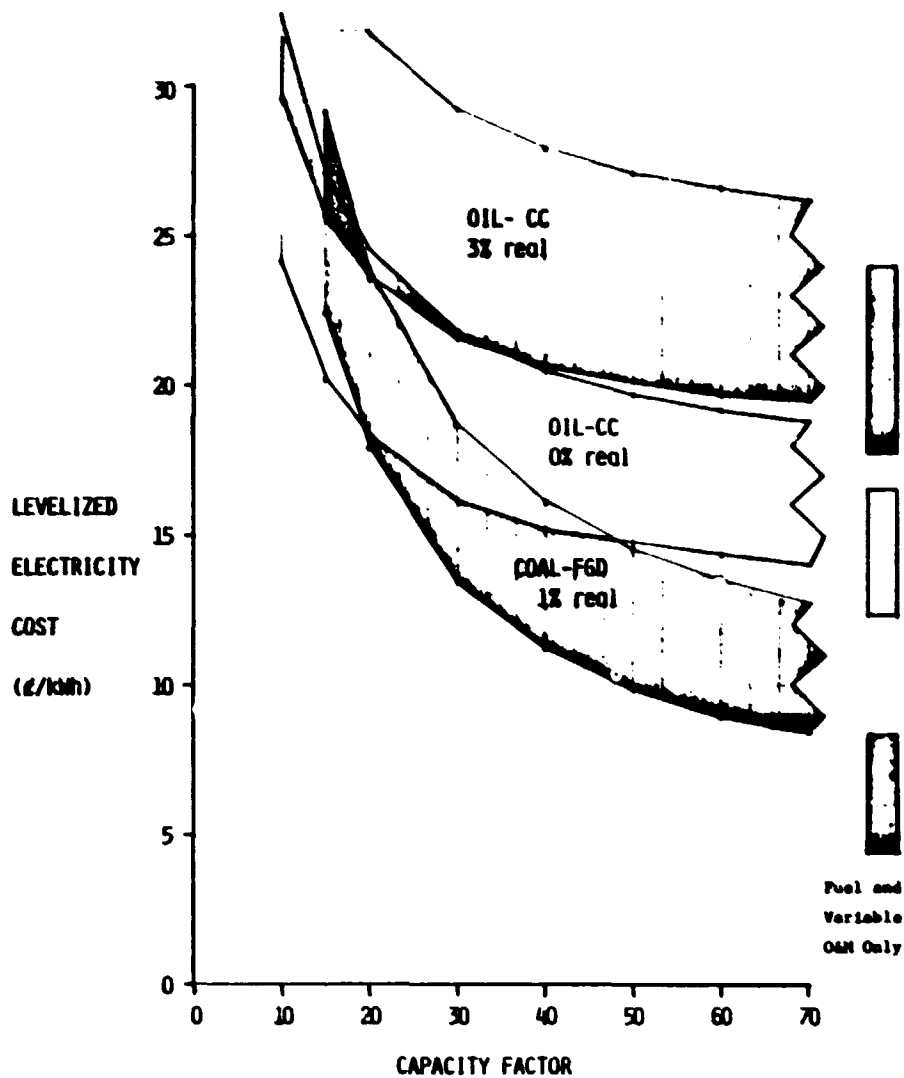
PLENARY SESSION: R.W. TAYLOR

Conventional Plant Characteristics (1982 \$)

	COAL (Subcritical 500MW)	OIL (Combined Cycle 250MW)
TOTAL CAPITAL REQUIREMENT	\$1113-1246/kW	\$496-653/kW
FIXED O&M	\$14.9-19.5/kW-yr	\$6.2-8.7/kW-yr
VARIABLE O&M	\$0.0024-0.0054/kWh	\$0.0014-0.0021/kWh
HEAT RATE	9970-10410	8600-8685
FUEL COST	\$1.50-2.60/10 ⁶ BTU	\$6.00-8.00/10 ⁶ BTU
REAL ESCALATION	1%/yr	0-3%/yr
INFLATION 8.5%/yr	DISCOUNT RATE 12.5%/yr	FCR = 0.18

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Range of Costs for Two New Generation Sources



Additional Sources of Competition

- NEW BASELOAD CAPACITY
- INCREASED REGIONAL POWER POOLING
- CONSERVATION AND LOAD MANAGEMENT
- STORAGE

Critical PV System Parameters

$$\begin{aligned} \text{SYSTEM EFFICIENCY} &= \text{? MODULES} \times \text{? BOS} \\ \text{SYSTEM COST} &= [\$ \text{MODULES} + \$ \text{BOS}] (1 + \text{INDIRECT}) + \$ \text{O\&M} \\ \text{SYSTEM VALUE} &= F (\text{UTILITY, PERFORMANCE}) \end{aligned}$$

Project Cost by Cost-Account Categories of Current Experiments

PROJECT	UPS		LICENT MFG.		RADAR STA.		SHOP. CTR.		HIGH SCH.		SCI. & ART	
COST CATEGORY	\$/W ²	\$/W _p	\$/W ²	\$/W _p	\$/W ²	\$/W _p	\$/W ²	\$/W _p	\$/W ²	\$/W _p	\$/W ²	\$/W _p
ENGINEERING	593	10.56	329	3.09	76	1.25	560	8.41	495	7.42	373	3.06
PV MODULES	576	10.23	1454	11.63	1114	18.33	753	11.32	725	10.25	1435	11.72
STRUCTURE	90	1.60	305	2.06	41	0.67	44	0.66	46	0.69	277	2.27
FOUNDATION	18	0.32	127	1.14	30	0.50	70	1.05	121	1.81	84	0.60
CIVIL WORK	54	0.96	(1)	(1)	85	1.40	137	2.05	178	2.67	195	1.60
ELECTRICAL	219	3.91	76	0.71	86	1.42	173	2.59	231	3.46	104	0.85
PLUM. COND. & CYCL.	100	1.91	183	1.71	76	1.25	180	2.70	159	2.38	56	0.46
BUILDINGS	54	0.96	(2)	(2)	18	0.47	38	0.57	20	0.29	(2)	(2)
TOTAL	1712	30.45	2469	23.14	1536	25.28	1955	29.35	1975	29.58	2524	20.70

NOTES: (1) ROOF-MOUNTED. (2) CONTROL LOCATED IN APPLICATION BUILDING. (3) ROOF-MOUNTED, REEROOF COST.

Central-Station Balance-of-System Cost Summary (December 1982 \$)

ITEM	FLAT PLATE		CONCENTRATOR	
	<u>\$/M²</u>	<u>\$/KW</u>	<u>\$/M²</u>	<u>\$/KW</u>
ARRAY STRUCTURE	28.6		•	
MODULE INSTALLATION	7.1		13	
FOUNDATION	5.3		17	
LAND	1.0		2.6	
SITE PREPARATION	8		15	
ROADS, FENCES, OTHER CIVIL	1.7		2.9	
DC SUBSYSTEM		24		73
POWER CONDITIONING		93		93
AC SUBSYSTEM		12		15
SWITCHYARD		14		14
STATION POWER	0.3		0.8	
INSTRUMENTATION	1		3.5	
GROUNDING	0.9		1.3	
SURGE PROTECTION	4		4	
TOTAL BOS FIELD COST	58	143	60	195

*ARRAY STRUCTURE & TRACKING INCLUDED WITH MODULE COST

Balance-of-System Efficiencies (%)

ITEM	FLATPLATE	CONCENTRATOR
MODULE DEGRADATION	95	95
DIRT ACCUMULATION	95	95
MODULE MISMATCH	97	97
INTERARRAY SHADOWING	98.5	99.9
DC SUBSYSTEM	99.4	98.9
POWER CONDITIONING	95	95
AC SUBSYSTEM	99.5	99
SWITCHYARD	99	99
STATION POWER	99.9	99.9
TOTAL	90	80

Operating and Maintenance (\$/m²-yr)

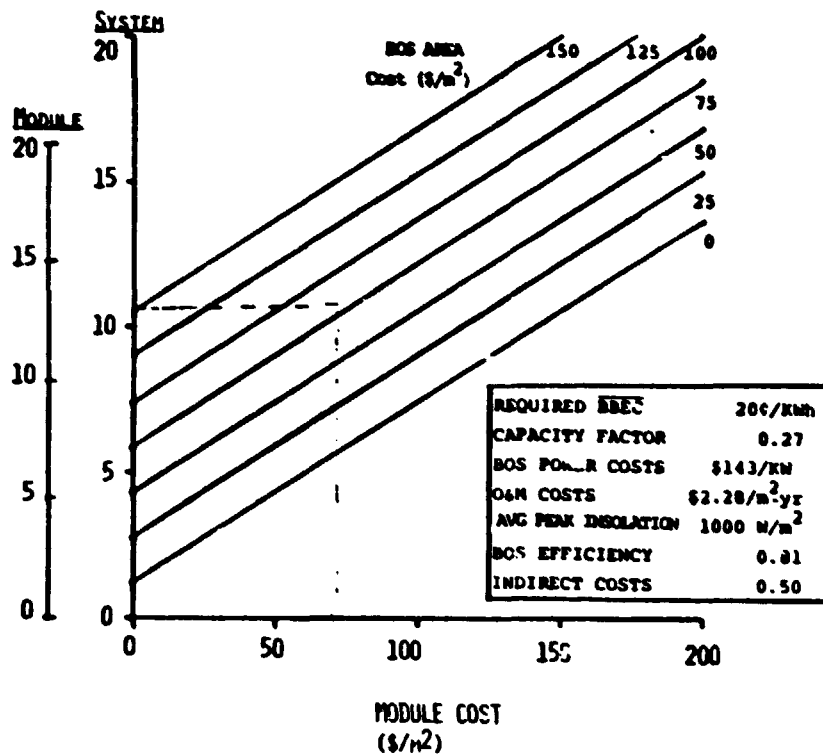
<u>ITEM</u>	<u>FLATPLATE</u>	<u>CONCENTRATOR</u>
OPERATORS	0.54	0.54
PLANT MAINTENANCE	0.96	1.36
ARRAY CLEANING (~1/MO)	0.51	0.51
MODULE REPLACEMENT (0.2%/YR)	0.27	0.28
	<u>2.28</u>	<u>2.69</u>

Indirect Costs

OWNER'S COSTS (EXCLUDING LAND)	6%
A & E FEE (MINIMAL MODULE CHECKOUT)	6%
CONTINGENCY	20%
INTEREST DURING CONSTRUCTION (3 YR CONSTRUCTION PERIOD)	12%
	<u>50%</u>

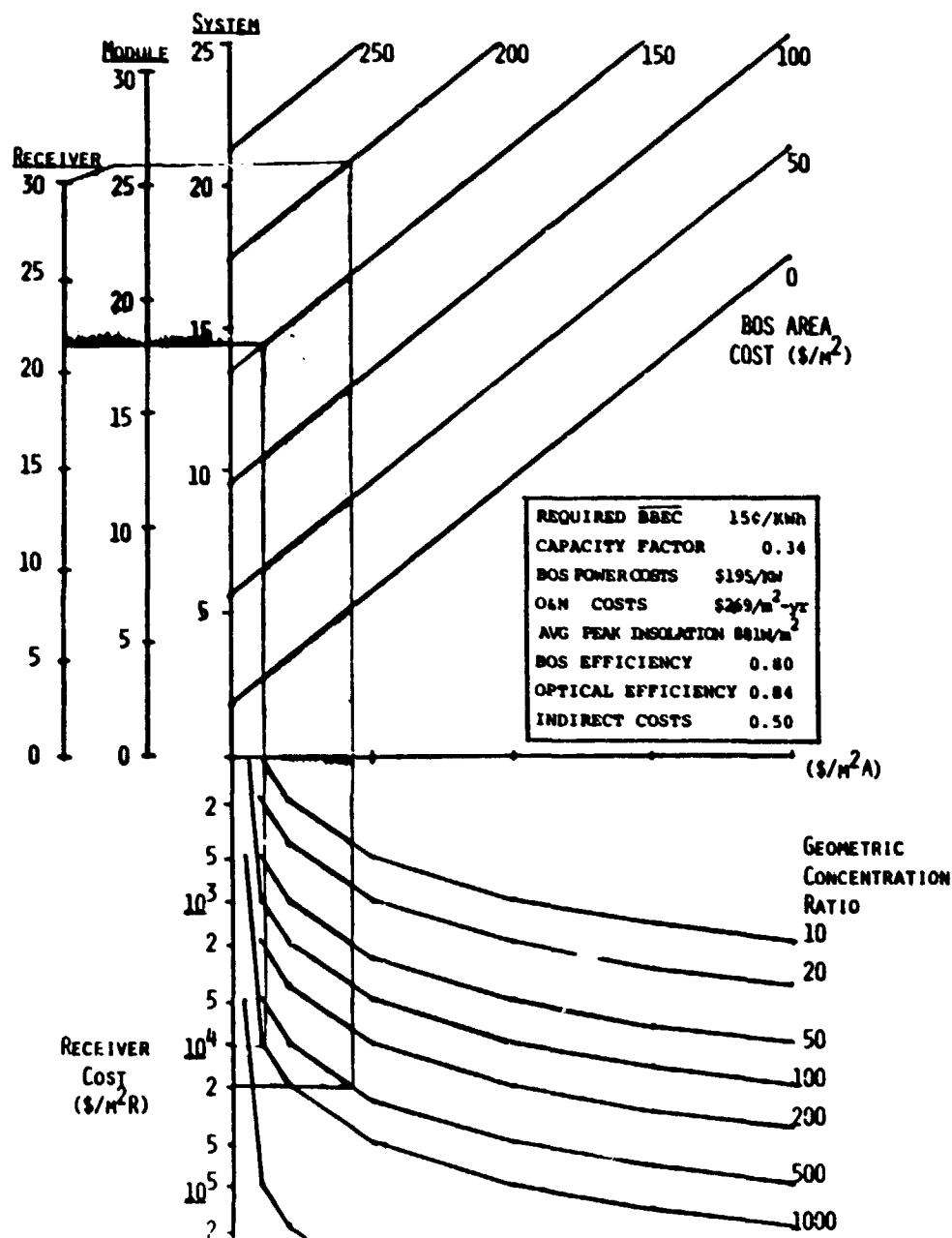
CONCENTRATOR
OF POOR QUALITY

Flat-Plate Cost-Efficiency Tradeoff



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Concentrator Cost-Efficiency Tradeoff



Comparison of Typical Efficiency Ranges

THEORETICAL POSSIBLE

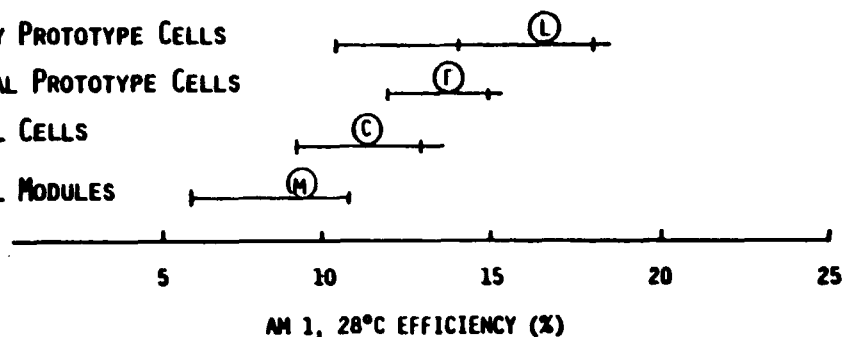
(T)

LABORATORY PROTOTYPE CELLS

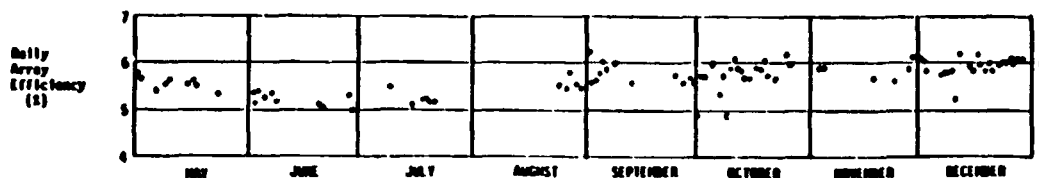
FIELD TRIAL PROTOTYPE CELLS

COMMERCIAL CELLS

COMMERCIAL MODULES



Daily Performance of Lovington Array During 1981



N83 10515 D10-44

ROOFTOP APPLICATIONS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

E. Kern ✓

PV Array Refinement and Innovation

- EFFECTIVE MOUNTING TECHNIQUES FOR NEW CONSTRUCTION AND RETROFIT
- AREA EFFICIENCY ENHANCEMENT
 - ARRAY COOLING
 - CELL INTERCONNECTION
 - FIXED REFLECTORS
- AMORPHOUS MATERIALS
 - REVOLUTIONARY OR EVOLUTIONARY MOUNTING?
- FULL-SCALE EXPERIMENTS ON RETROFIT APPLICATIONS

Power Conditioning Refinement and Innovation

- STANDARDS ON POWER QUALITY; VALIDATE EFFECTS
- INSPECTION AND CONTROLLED TEST PROCEDURES

Essential Research Needs: Rooftop Applications

<u>AREA</u>	<u>STATUS</u>	<u>NEED</u>
COST REDUCTION	<ul style="list-style-type: none"> • STALLED AT \$10/W 	<ul style="list-style-type: none"> • MODULE COSTS (PRICES) • FEDERAL POLICY ISSUES
UTILITY INTEGRATION	<ul style="list-style-type: none"> • RED HERRING (?) 	<ul style="list-style-type: none"> • EXPERIMENTS TO VERIFY ANALYSES
RELIABILITY	<ul style="list-style-type: none"> • ARRAYS ADEQUATE • POWER CONDITIONERS HAVE PROBLEMS • NEW UNITS PROMISING 	<ul style="list-style-type: none"> • ACCELERATED LIFE TESTING • LONG-TERM ENDURANCE DATA
PERFORMANCE PREDICTION	<ul style="list-style-type: none"> • PV POWER PRODUCTION ADEQUATE • SOILING, RESIDENTIAL LOADS UNDER STUDY 	
PV ARRAY	<ul style="list-style-type: none"> • ADEQUATE DESIGNS UNDER TEST • REFINEMENTS LIKELY 	<ul style="list-style-type: none"> • RETROFIT EXPERIMENTS • MOUNTING FOR AMORPHOUS (?)
POWER CONDITIONING	<ul style="list-style-type: none"> • DRAFT STANDARDS ABOUND • PRIVATE SECTOR ACTIVE 	<ul style="list-style-type: none"> • IMPLEMENT SUB-SYSTEM TEST PROCEDURES

System Cost Reduction

- PV MODULE PRICES NOT DECLINING
- RESIDENTIAL ELECTRICITY PRICES NOT INCREASING
- DISTRIBUTED GENERATION (PURPA) UNDER ATTACK

Research Areas: Rooftop Applications

- COST REDUCTION
- UTILITY INTEGRATION
- RELIABILITY
- PERFORMANCE PREDICTION
- PV ARRAY
- POWER CONDITIONING AND CONTROL

Electric Utility Integration

- DISTRIBUTION SYSTEM SAFETY VERIFICATION
- POWER QUALITY EFFECTS MEASUREMENTS
- FEEDER DESIGN TO ACCOMMODATE PV
- TEMPORAL AND SPATIAL INSOLATION EFFECTS
CAPACITY DISPATCH
TRANSMISSION
DISTRIBUTION

PV System Performance Prediction

- EXTEND AND VALIDATE SIMULATION TECHNIQUES
LOAD CHARACTERIZATION
SOILING AND SELF-CLEANING
- LONG-TERM ESTIMATES FOR ARBITRARY SITES
INTERPOLATION BETWEEN SOLMET TMY SITES
ENLIGHTENED CONSUMER CHOICES
UTILITY CAPACITY PLANNING
- SHORT- AND MEDIUM-TERM FORECASTS
UTILITY CAPACITY DISPATCHING
UTILITY SCHEDULED MAINTENANCE PLANNING

PV System Reliability

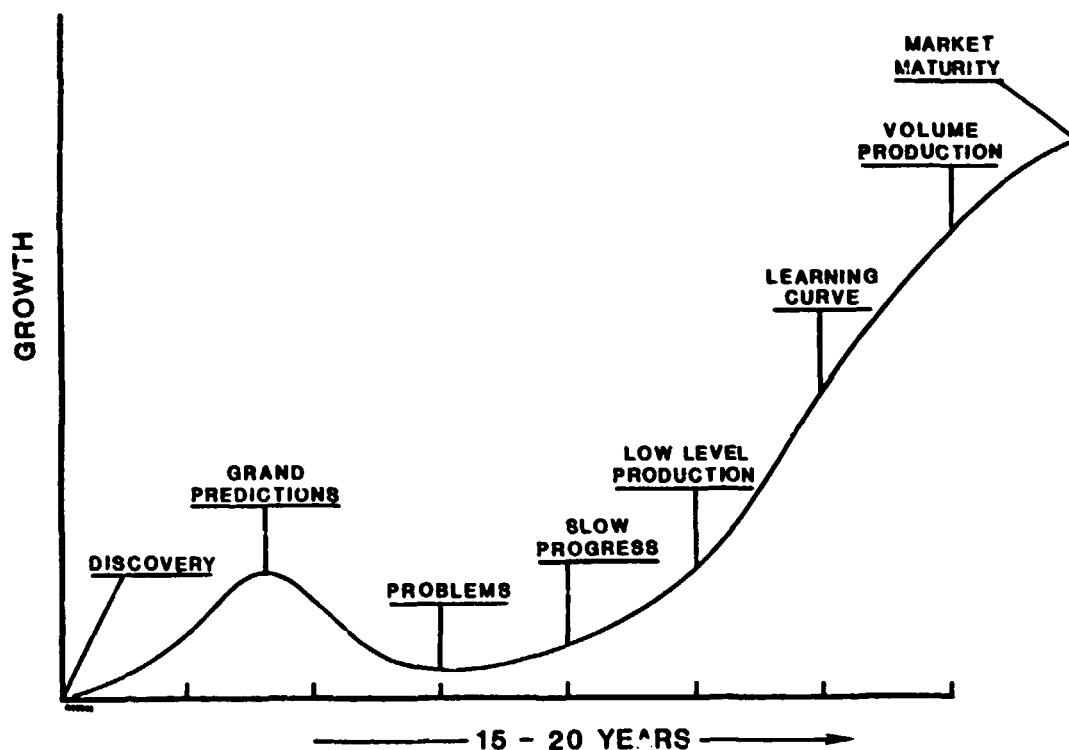
- **PV ARRAY ENDURANCE**
 - CLIMATE EXTREMES OVER MULTI-YEAR PERIODS**
 - DEVELOP AND VALIDATE ACCELERATED LIFE TESTING**
- **POWER CONDITIONER CONTROL**
 - WEATHER EXTREMES**
 - LOAD EXTREMES**
 - UTILITY VOLTAGE FLUCTUATIONS**

PV RESEARCH NEEDS: INDUSTRY PERSPECTIVE

SPIRE CORP.

R. Little

PV Product Growth Stages



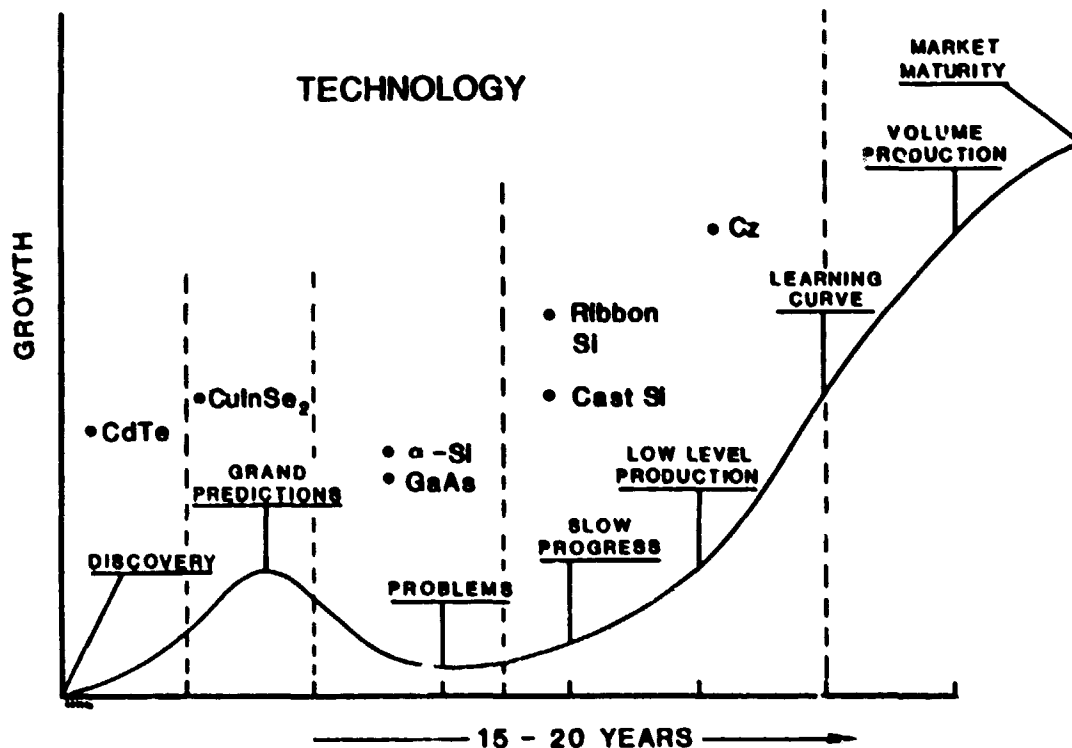
E-O Technologies

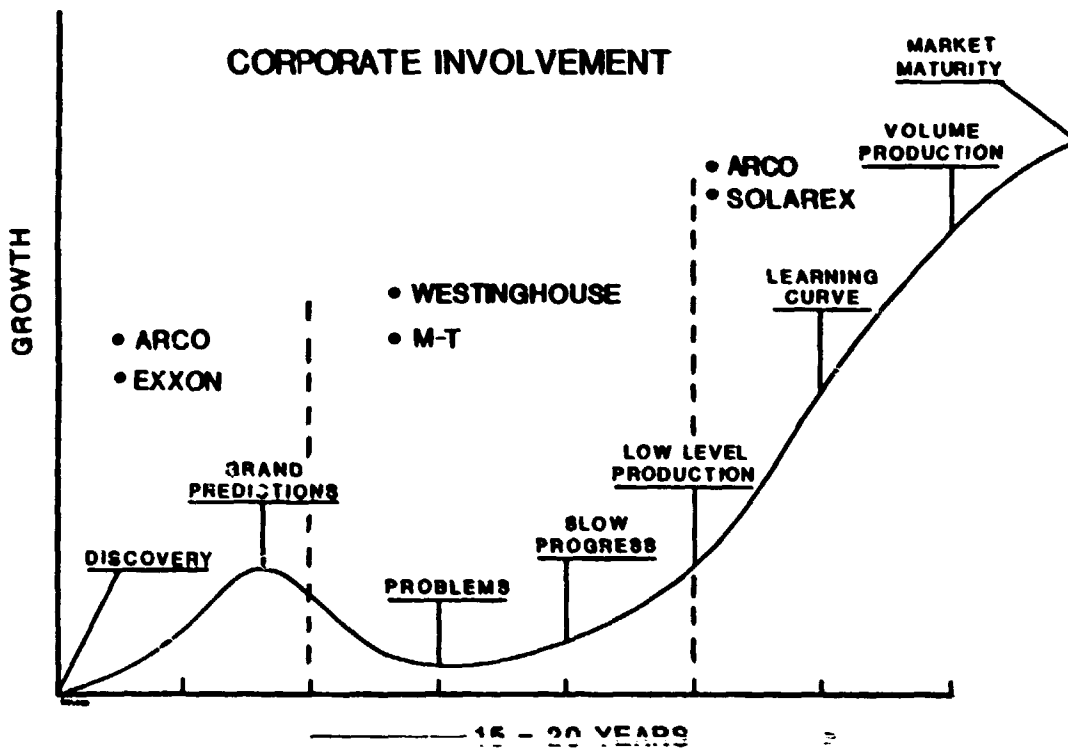
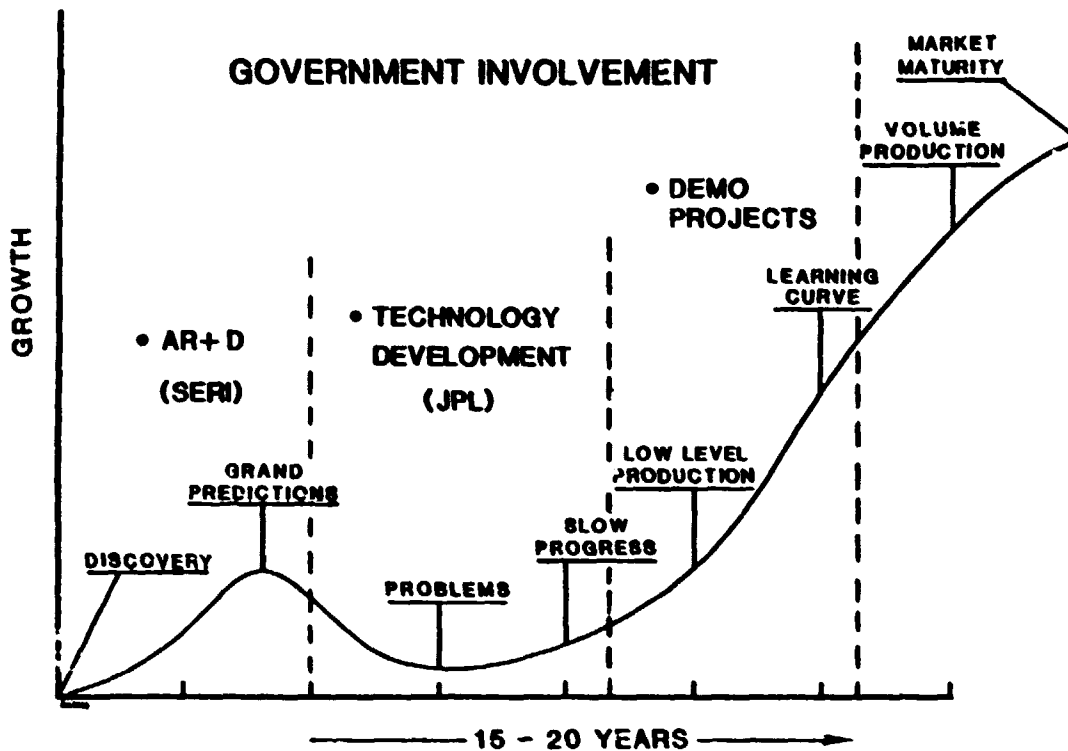
15 YEAR CYCLE

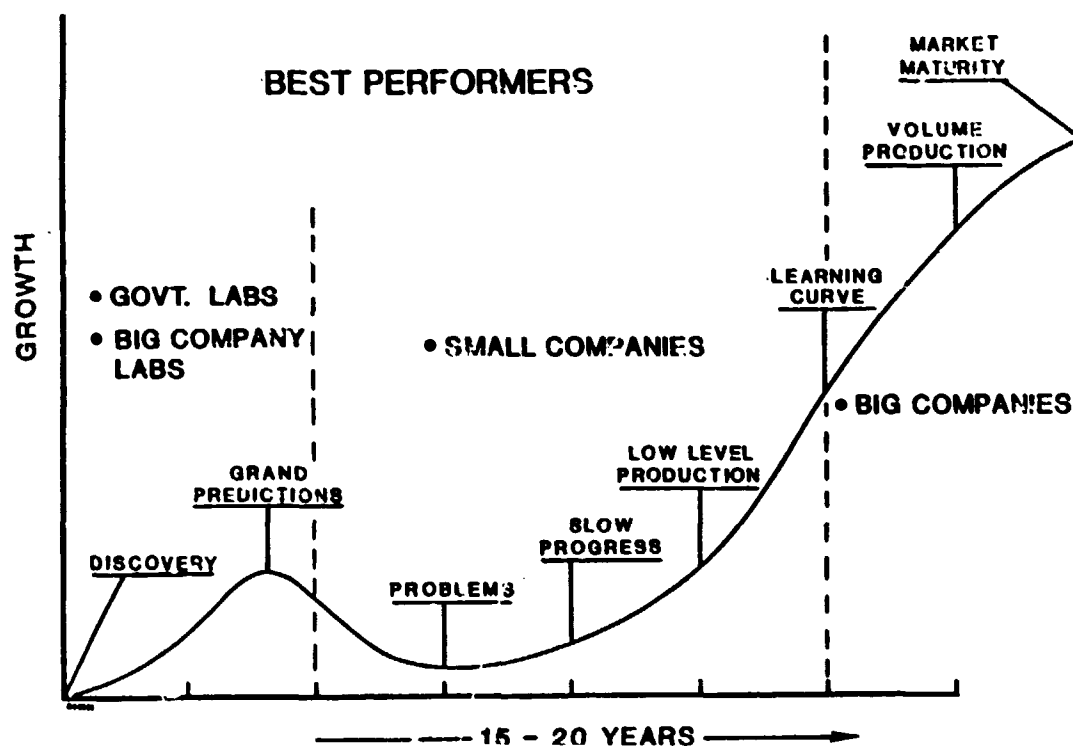
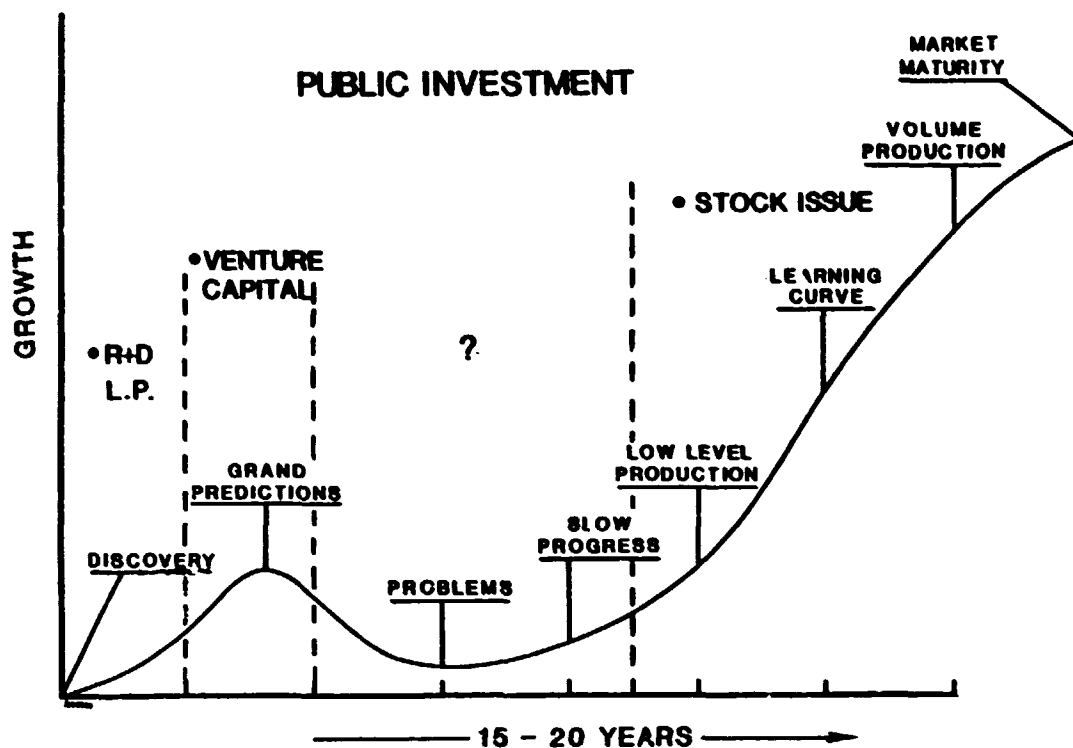
- | | |
|-----------------------|-----------------------|
| • VIDEO DISCS | • SOLID STATE IMAGERS |
| • LED's | • AUTOMATIC BONDING |
| • HgCdTe IR DETECTORS | • FIBER OPTICS |
| • LATV | • E-BEAM LITHOGRAPHY |
| • BUBBLE MEMORIES | • FLAT PANEL DISPLAYS |
| • GaAs ELECTRONICS | |

L.A. MURRAY, ELECTRO-OPTICAL SYSTEMS DESIGN, OCTOBER 1981

PV Product Growth Stages







PHOTOVOLTAIC RESEARCH NEEDS: INDUSTRY PERSPECTIVE

MOBIL TYCO SOLAR ENERGY CORP.

K.V. Ravi ✓
(Presented by J.P. Kalejs)

Research Objectives of PV Industry

- TO UNDERSTAND, DEVELOP AND IMPLEMENT NEW PROCESSES FOR THE PURPOSES OF MANUFACTURING COST REDUCTION AND REVENUE ENHANCEMENT.
- TO DEVELOP DETAILED UNDERSTANDING OF ONGOING PROCESSES TO MAINTAIN INTEGRITY OF THE PROCESS AND TO ENHANCE YIELDS AND EFFICIENCIES.
- TO MAINTAIN AWARENESS OF NEW DEVELOPMENTS AND CAPITALIZE ON THESE TO SUSTAIN AND ENHANCE MARKET SHARE AND PROFITABILITY.

Features of R&D Geared Toward Industry Needs

- RELATIVELY SHORT RANGE (1-5 YEARS).
- INTERACTIVE - INDUSTRY, GOVERNMENT, UNIVERSITIES.
- RESEARCH IS MORE DEVELOPMENTAL IN NATURE AND LESS FUNDAMENTAL.
- RESEARCH NEEDS TO BE GENERAL IN NATURE RATHER THAN PRODUCT OR PROCESS SPECIFIC - PROBLEMS PERTAINING TO PROPRIETARY TECHNOLOGY.
- DIFFICULTY OF TECHNOLOGY TRANSFER (EXAMPLE OF SUCCESSFUL TECHNOLOGY TRANSFER IS THE EVA ENCAPSULATION TECHNOLOGY DEVELOPED UNDER DOE/JPL SPONSORSHIP).

Research Categories

MATERIALS

DEVICES

PROCESSES

RELIABILITY

Materials Research

MATERIALS PRODUCTION

- RATE EFFECTS IN CRYSTAL GROWTH.
- MENISCUS AND INTERFACE PHENOMENA.
- STRESS PROBLEMS IN HIGH RATE, LARGE AREA SHEET GROWTH.
- IMPURITY INCORPORATION AND DISTRIBUTION EFFECTS AND MECHANISMS.

MATERIALS PROPERTIES

- ELECTRONIC PROPERTIES OF IMPERFECT AND IMPURE CRYSTALS.
- PROBLEMS PERTAINING TO INHOMOGENEOUS CRYSTALS.
- THE INFLUENCE OF CARBON AND OXYGEN IN SILICON ON ELECTRONIC PROPERTIES.
- INFLUENCE OF THERMAL PROCESSES ON ELECTRONIC AND MECHANICAL PROPERTIES.
- ELECTRONIC EFFECTS OF GRAIN BOUNDARIES, DISLOCATIONS, IMPURITY INHOMOGENEITIES.

MATERIALS ANALYSIS

- CENTRALIZED ANALYTICAL AND CHARACTERIZATION SERVICES INCLUDING CHEMICAL, PHYSICAL AND ELECTRICAL CHARACTERIZATION.
- NON-DESTRUCTIVE TECHNIQUES FOR RAPID MATERIALS PROPERTY ANALYSIS INCLUDING LIFETIME MEASUREMENTS, CRACK DETECTION IN SOLAR CELLS, ETC.
- CHARACTERIZATION OF MATERIALS PRONE TO HIGH IMPURITY AND DEFECT CONCENTRATIONS.

Device Research

- ANALYSIS AND DEVELOPMENT OF DEVICE STRUCTURES FOR MAXIMIZING CONVERSION EFFICIENCIES.
- R & D ON CONDUCTING OXIDES, HETEROJUNCTIONS, JUNCTION PROFILES, GRADED JUNCTIONS, VOLTAGE ENHANCEMENT TECHNIQUES.
- DEVICE CONFIGURATIONS SUITED TO MATERIAL PRONE TO CONTAIN A HIGH DENSITY OF IMPERFECTIONS AND IMPURITIES.

Process Research

PROCESS TECHNOLOGY

- RAPID PROCESSING TECHNOLOGY
 - HIGH SPEED JUNCTION FORMATION AND METALLIZATION TECHNOLOGIES AND METHODS FOR DEPOSITION OF MULTIPLE AR COATINGS, METAL CONTACTS.
- BEAM PROCESSING
 - LASERS, E-BEAMS, MICROWAVES FOR DIFFUSION, METALLIZATION, SINTERING, JUNCTION ISOLATION.
- MATERIALS ENGINEERING TO DEVELOP TECHNIQUES SUCH AS INTRINSIC GETTERING, SELECTIVE HEATING OF CRYSTALS FOR PERFORMANCE ENHANCEMENT.
- DEVELOPMENT OF BASE METAL PASTES FOR SCREEN PRINTED CONTACTS. LASER ASSISTED PLATING TECHNIQUES.
 - AUTOMATION AND MATERIALS HANDLING
- PROCESS DEVELOPMENTS GEARED TOWARDS THE NEEDS OF AUTOMATION AND LARGE SCALE MANUFACTURE.
- YIELD ENHANCEMENT TECHNIQUES.
- TECHNOLOGY TO DETECT BROKEN CELLS IN PROCESS.
- FUNDAMENTAL UNDERSTANDING OF FRACTURE MECHANICS OF SILICON, RESIDUAL STRESS EFFECTS, THICKNESS EFFECTS AND EDGE QUALITY EFFECTS.

PLENARY SESSION: K.V. RAVI

Reliability

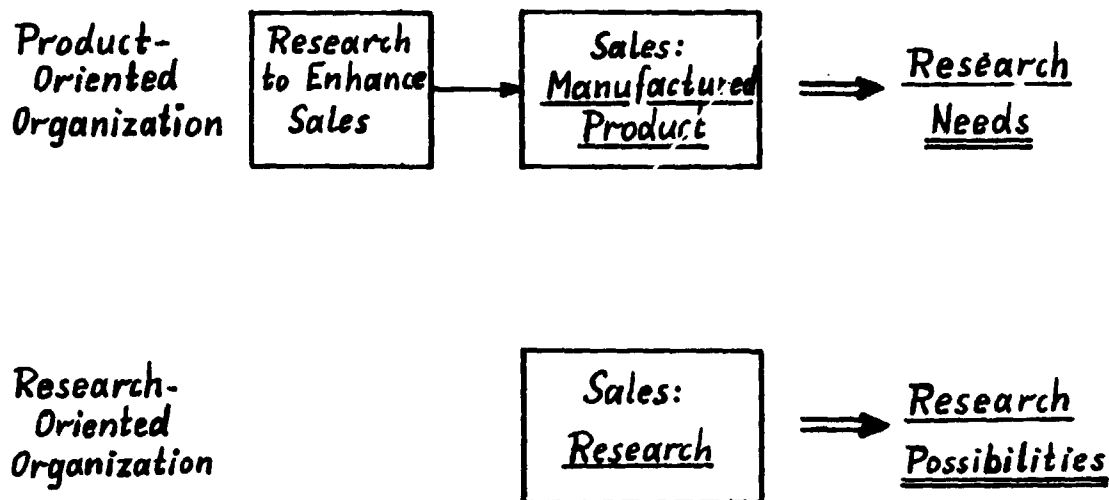
- FIELD TESTING OF MODULES.
- ESTABLISHMENT OF STANDARDS. CALIBRATION OF STANDARD CELLS.
- ACCELERATED CELL AND PANEL TESTING. WEAR OUT AND FAILURE MECHANISMS.
- RELIABILITY PHYSICS - R & D IN THE PHYSICS OF RELIABILITY OF MATERIALS, DEVICES, METALLIZATION SYSTEMS, INTERCONNECTS, PACKAGES.

RESEARCH POSSIBILITIES? NO! Needs for Research to Make PV Solar Energy Utilization Broadly Competitive

UNIVERSITY OF PENNSYLVANIA

M. Wolf ✓

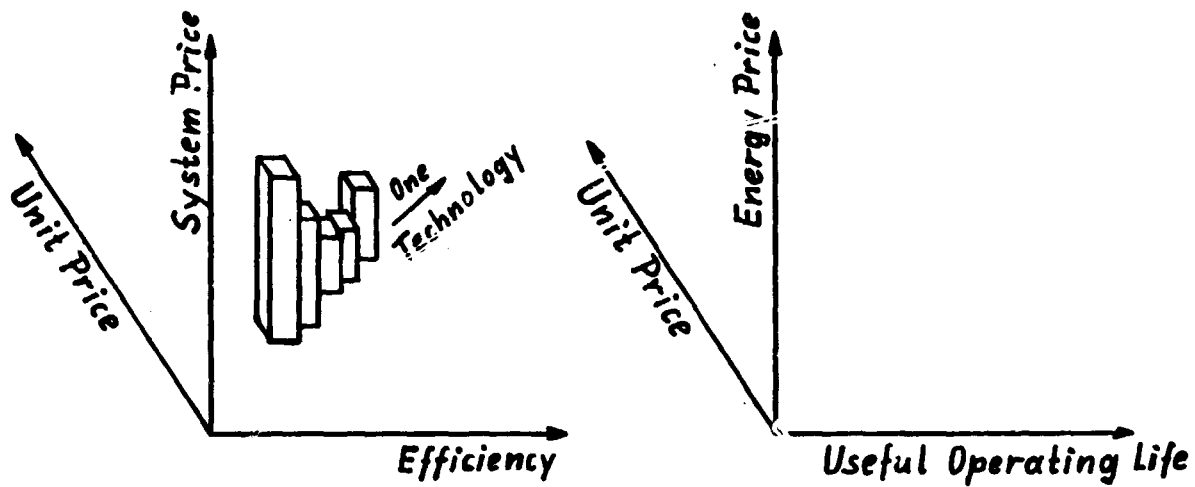
Two Types of Research Philosophies



MAJOR CRITERION
FOR
COMPETITIVENESS:
PRICE OF ELECTRIC ENERGY

PLENARY SESSION: M. WOLF

Multivariable Relationships



The Subsystems

- MODULE →
- LIGHT PROCESSOR (CONCENTRATOR, TRACKER)
 - CONVERTER ARRAY
 - POWER CONDITIONING
 - ENERGY STORAGE
 - CONTROL. PROTECTION
 - AUXILIARY ENERGY

System Characteristics Determine Market

SYSTEM TYPE	LIKELY USE	MARKET SIZE	MOST LIKELY CANDIDATES
HIGH CONCENTRATION, TRACKING VERY HIGH EFFICIENCY CONVERTER	ARID CLIMATES, CENTRAL STATION (ATTENDED OPERATION)	LIMITED	SINGLE CRYSTAL $Al_xGa_{1-x}As$ / GaAs (SINGLE CRYSTAL Si?) MULTI-BANDGAP SYSTEMS
FLAT-PLATE, HIGH EFFICIENCY LONG LIFE	ALL USES, COMMERCIAL INSTALLATION	LARGEST	SINGLE CRYSTAL Si (MULTI-BANDGAP SYSTEMS?)
VERY LOW COST, LOW EFFICIENCY LIMITED LIFE	PRIMARILY RESIDENTIAL, DO-IT-YOURSELF INSTALLATION	LIMITED	THIN-FILM A-Si OTHER THIN FILM SEMICONDUCT. (Cu_2InSe/CdS ?)

Research Needs on BOS

SUBSYSTEM	NEEDED ATTRIBUTES	PAYOFF	RISK	TIME RANGE TO ATTAINMENT
POWER CONDITIONING	LOW PRICE, HIGH EFFICIENCY	I	L	S TO I
CONTROL, PROTECTION	LOW PRICE, SIMPLE	I	L	S
ENERGY STORAGE	LOW PRICE LONG LIFE HIGH EFFICIENCY HIGH DISCHARGE RATE DEEP CYCLE CAPABILITY	VH	H	L
FIELD INSTALLATION	LOW PRICE	VH	VH	?
HIGH-RATIO CONCENTRATOR	LOW PRICE LOW MAINTENANCE	I	H	I
AUXILIARY ENERGY	LOW PRICE	H TO VH	VH	L

S = SMALL OR SHORT
I = INTERMEDIATE

H = HIGH
VH = VERY HIGH

L = LONG
RISK = INVERSE PROBABILITY FOR
ATTAINMENT OF EXPECTED PAYOFF

Research Needs on Modules

ITEM	NEEDED ATTRIBUTES	PAYOFF	RISK	TIME TO ATTAINMENT
CELL (MANUF'G PROCESS)	COST REDUCTION 10-20 TIMES	VH	I	S TO I
CELL	EFFICIENCY INCREASE 25 TO 66% SINGLE CELLS TO 300% MULTI-BANDGAP SYSTEMS (WILL REQUIRE MODIFIED CELL PROCESSING)	VH	I VH	S TO I L
MODULE	≥ 20 YEAR LIFE } COST REDUCTION } COMPATIBLE?	VH	I	I TO L

Current Status of Major Module Processes

TECHNOLOGY AREA	APPROACH	EXPECTED RESULTS	STATUS
<u>SILICON SOLAR/MODULES:</u>			
LOW COST PURIFICATION	SiH ₄ PROCESS	~\$14.-/KG SEMICONDUCTOR- GRADE SI	PRIVATE INDUSTRY (UNION CARBIDE) GOES INTO PILOT PLANT OPERATION.
	Si H ₂ Cl ₂ PROCESS	~\$25.-/KG SEMICONDUCTOR GRADE SI	PRIVATE INDUSTRY (HEMLOCK SEMICONDUCTOR CONVERTS EXISTING SiHCl ₃ PLANT
SHEET GENERATION	(SEMI-) CONTINUOUS AUTOMATED Cz X-TAL GROWTH	150KG/CRUCIBLE, 15 CM DIA	NEARLY PRODUCTION READY BOTTLENECK: SLICING
	SEMICRYSTAL SI	LOWER COST THAN Cz, COMPARABLE PERFORMANCE	PRODUCTION COST/PERFORMANCE EXPERIENCE NEEDED. BOTTLENECK: SLICING
	SLICING	HIGH THROUGHPUT, LOW KERF, LOW COST	LITTLE ADVANCEMENT. <u>PROBLEM AREA.</u>
	RIBBON GROWTH: EFG	LOW COST, Cz COMPATIBLE CELL PERFORMANCE	PILOT PRODUCTION CELL EFFICIENCY STILL TOO LOW

PLENARY SESSION: M. WOLF

TECHNOLOGY AREA	APPROACH	EXPECTED RESULTS	STATUS
	WEB-DENDRITE	LOW COST, CZ COMPATIBLE CELL PERFORMANCE	CZ COMPATIBLE EFFICIENCY PROVEN. ONLY MATERIAL WITH INTERNAL GETTERING. PRE-PILOT STAGE. PRODUCTION COST EXPERIENCE NEEDED. WILL PRIVATE INDUSTRY GO AHEAD?
CELL FABRICATION:	PROCESS SIMPLIFI- CATION, BY-PRODUCT REDUCTION, AUTOMA- TION	\$0.5 TO 1.5/W _p MODULES OF 14-17% EFFICIENCY	CONSIDERABLE TECHNOLOGY ADVANCE- MENTS MADE. ~\$10/W _p AT 7-12% EFFICIENCY. CONTINUED SLOW PROGRESS IN PRIVATE INDUSTRY. STAGNATION AT A PRICE LEVEL OF 5-10\$/W _p AHEAD?
MODULE ASSEMBLY	BETTER MATERIAL SELECTION, AUTOMA- TION	DTO 20-YEAR LIFE	DTO COST/LIFE TRADE-OFF UNCERTAIN.
<u>A Si</u>	THIN FILM PROCESSES, LOW-COST ENCAPSULA- TION	< \$0.5/W _p LIMITED EFFI- CIENCY	RESEARCH STAGE. PRODUCTION IN JAPAN FOR CALCU- LATOR/WATCH MARKET
<u>AL_xGA_{1-x}As/GAAs</u>	SINGLE X-TAL CELLS.	HIGHER EFFICIENCY THAN Si CELLS, SUPERIOR HIGH TEMPERATURE PER- FORMANCE, BETTER RADIATION RESIS- TANCE FOR SPACE CELLS	PILOT LINE QUANTITIES AVAILABLE PRIMARILY CONCENTRATOR AND SPACE CELLS. MAY FORM COMPONENT IN MULTI- BANDGAP SYSTEM
Cu ₂ S/CdS CELLS	THIN FILM PROCESSES, LOW-COST ENCAPSULA- TION	< \$0.5/W _p . LIMITED EFFI- CIENCY, LIFE	TECHNOLOGY BEING ABANDONED?
Cu ₂ InSe/CdS CELLS	DTO	HIGHER EFFICIENCY, LONGER LIFE THAN Cu ₂ S/CdS	RESEARCH STAGE, MAY FORM COMPONENT IN MULTI-BANDGAP SYSTEM.
ALL OTHER COM- POUND SEMICON- DUCTORS	MOSTLY THIN FILM PROCESSES	MOSTLY LOW COST	VARIOUS LEVELS OF RESEARCH. LIKELY REDUNDANT WITH FURTHER ADVANCED APPROACHES. SOME CANDIDATES FOR MULTI- BANDGAP SYSTEMS.

Who Pays What Research?

SHORT RANGE, LOW RISK	IN BETWEEN	LONG RANGE, HIGH RISK GOVERNMENT
<u>MANUFACTURING INDUSTRY</u>	<u>MANUFACTURING INDUSTRY</u>	<u>GOVERNMENT</u>
GRADUAL PROCESS ADVANCEMENT, AUTOMATION FOR COST REDUCTION.	SOME THIN FILM APPROACHES (HOW LONG, IF MARKET DOES NOT DEVELOP SOON?)	SI-CELLS: EFFICIENCY >20% (AM1)
SMALL STEPS TO EFFICIENCY IMPROVEMENT, EXTENSION OF OPERATING LIFE	<u>?WHO?</u>	MULTI-BANDGAP SYSTEMS GRAIN BOUNDARY RESEARCH THIN FILM DEVICES (?) BATTERIES/FUEL CELLS
GRADUAL POWER CONDITIONING PROGRESS	RADICAL PROCESS ADVANCEMENT RELIABILITY DEVELOPMENT STANDARDIZATION CONCENTRATORS FIELD INSTALLATION	<u>MANUFACTURING INDUSTRY</u> A-SI APPROACHES

Identifiable Research Needs for Efficiency Improvement

SINGLE CRYSTAL SI CELLS

GOAL	NEEDED UNDERSTANDING	FURTHER ACTIONS
LONGER MINORITY CARRIER LIFETIME Si	CRYSTAL STRUCTURE, ROLE OF IMPURITIES (HEAVY METALS?) ROLE OF COMPLEXES (O ₂ , C, STRUCTURE DEFECTS?) ORIGIN OF DEFECTS, IMPURITIES INTRODUCTION MECHANISM OF DEFECTS, IMPURITIES POTENTIAL AND LIMITS OF GETTERING INFLUENCE OF POST-GROWTH HEATING, LIGHT	PROCESS CONTROL IN CRYSTAL (RIBBON) GROWTH PROPER POST-GROWTH PROCESS SELECTION

GOAL	NEEDED UNDERSTANDING	FURTHER ACTIONS
<u>SINGLE CRYSTAL SI CELLS, CONTINUED</u>		
SURFACE PASSIVATION	EXACT MECHANISM REQUIREMENTS ON PASSIV- ATION LAYERS WAYS TO MEET REQUIREMENTS OPTICAL PROPERTIES OF PASSIVATION LAYERS INTERACTIONS WITH AR COATINGS	PROCESS DEVELOP- MENT
ATTAINMENT OF PRE- DESIGNED DEVICE STRUCTURE	EFFECTS RESULTING FROM INDIVIDUAL PROCESSES (DIFFUSION, CVD OR LPE EPI, ETC) "LOW TEMPERATURE" PRO- CESSING FEASIBLE? LIFETIME MAINTENANCE THROUGHOUT PROCESSES? OR RECOVERY? SIMPLER PROCESS METHODS?	
"CLOSED LOOP DESIGN"	ANALYSIS: ALL PARAMETERS WHICH INFLUENCE PERFORMANCE OR ENTER MODELLING LACKING: RELIABLE MEASUREMENTS OF FRONT LAYER DIFFUSION LENGTH; MEASUREMENT OF: DIFFUSION LENGTH OF MORE HEAVILY DOPED LAYERS; EFFECTIVENESS OF HIGH/LOW JUNCTIONS; FRONT SURFACE RECOMBINATION VELOCITY. TWO METHODS BASED ON COM- PLETELY DIFFERENT EFFECTS SHOULD BE AVAILABLE FOR COR- ROBORATION OF RESULTS. UNDERSTANDING OF HEAVY-DOPING EFFECTS TO ALLOW MORE PRECISE MODELLING, ASCERTAIN ULTI- MATELY ACHIEVABLE EFFICIENCY.	

POLYCRYSTAL DEVICES

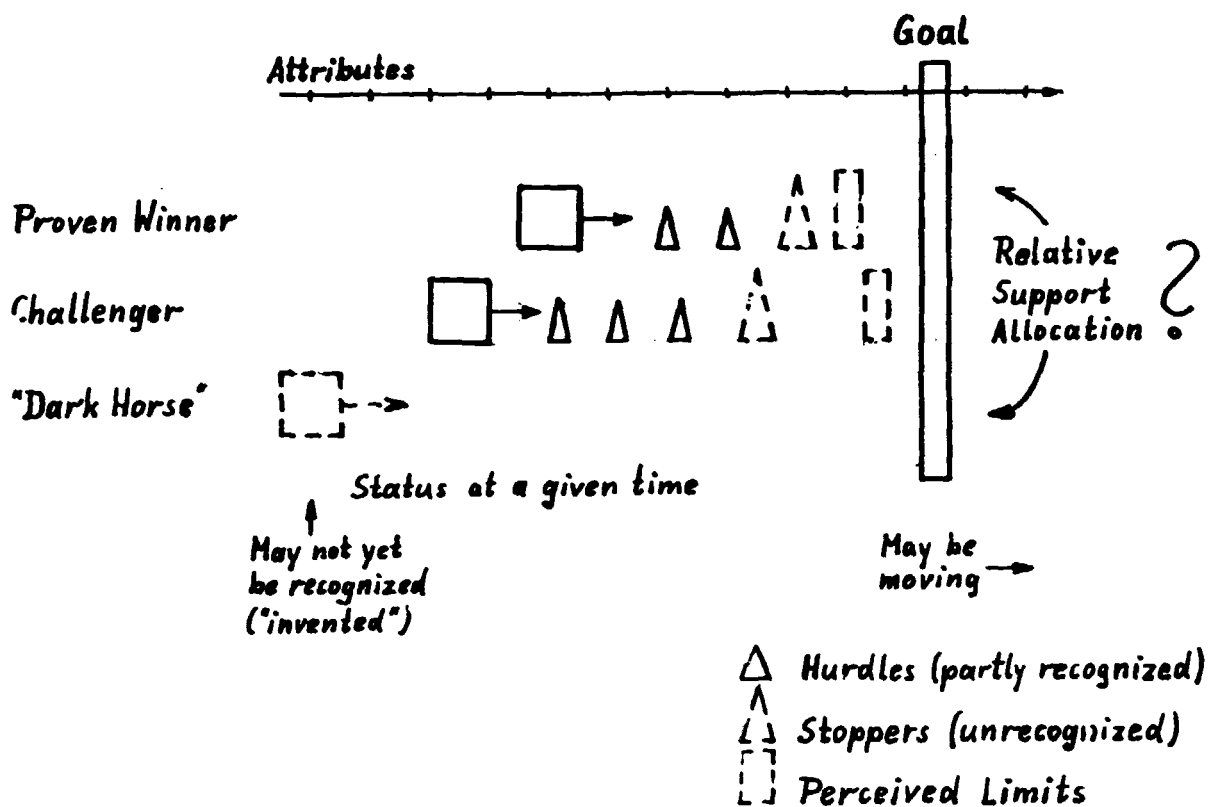
ALL THE ABOVE, PLUS:
EFFECTS OF GRAIN BOUNDARIES
ON DEVICE PERFORMANCE;
CONTROL OF ELECTRICAL EFFECTS
OF GRAIN BOUNDARIES
DEVICE DESIGN TO MINIMIZE
EFFECTS OF GRAIN BOUNDARIES

GOAL	NEEDED UNDERSTANDING	FURTHER ACTIONS
	<u>COMPOUND SEMICONDUCTORS</u> (INCL. AMORPHOUS Si:H, ETC)	
	ALL OF ABOVE, EXCEPT FOR GRAIN BOUNDARIES, WHERE NOT APPLICABLE. PLUS: LEVEL OF EXISTING KNOWL- EDGE GENERALLY MUCH LOWER THAN FOR Si EFFECTS OF STOICHIOMETRY DEVI- ATIONS. CONTROL OF FABRICATION PROCESSES.	

MULTI-BANDGAP SYSTEMS

ALL OF ABOVE; EXCEPT FOR
 GRAIN BOUNDARY EFFECTS, WHERE
 NOT APPLICABLE. PLUS:
 INTERFACES BETWEEN CELLS OF
 DIFFERENT BANDGAP (TUNNEL-
 JUNCTIONS?)
 PROBLEMS OF MISMATCH BETWEEN
 CELLS UNDER DIFFERING INTENSITY,
 SPECTRAL DISTRIBUTION (AM),
 TEMPERATURE.

The Technology Race



EVALUATION OF ADVANCED R&D TOPICS IN PHOTOVOLTAICS

SOLAR ENERGY RESEARCH INSTITUTE

T. Surek ✓

Objective

- DEVELOP PRIORITIZED LIST OF ADVANCED R&D AREAS
IN PHOTOVOLTAICS TO ASSURE OPTIMAL USE OF LIMITED
FUNDS.

Approach

- IDENTIFY AR&D AREAS (SERI/JPL/SANDIA PV PROGRAM MANAGERS/RESEARCHERS,
OMB GUIDELINES, SPEAC AND ERAB REPORTS)
- DEVELOP EVALUATION CRITERIA
- SOLICIT EVALUATIONS FROM PV EXPERTS IN INDUSTRY, UNIVERSITIES AND
GOVERNMENT
- EVALUATE RESPONSES; IDENTIFY RELATIVE IMPORTANCE OF AR&D AREAS;
ALLOCATE FUNDING

AR&D Areas

- 35 AR&D ACTIVITIES WERE IDENTIFIED IN 10 MAJOR AREAS:
 - AMORPHOUS SILICON
 - CONCENTRATOR CELLS
 - CRYSTALLINE SILICON
 - HIGH EFFICIENCY: III-V AND RELATED AREAS
 - INNOVATIVE CONCEPTS
 - LUMINESCENT CONCENTRATORS
 - PHOTOELECTROCHEMICAL AREAS
 - SUPPORT RESEARCH
 - SYSTEMS AND MODULES
 - II-VI AND RELATED AREAS

Evaluation Criteria

● CONTRIBUTION TO BASIC SCIENTIFIC UNDERSTANDING:

<u>VERY LIKELY</u>	TO PRODUCE SIGNIFICANT ADVANCES, DISCOVERIES,...
<u>LIKELY</u>	TO ADD FUNDAMENTAL KNOWLEDGE
<u>NOT LIKELY</u>	TO ADD NEW KNOWLEDGE

● POTENTIAL IMPACT (IN 5 YEARS OR MORE) ON FURTHER TECHNOLOGY DEVELOPMENT BY PRIVATE INDUSTRY:

<u>EXCELLENT</u>	PROBABILITY OF SIGNIFICANT IMPACT
<u>PROBABLE</u>	THAT POSITIVE OR INDIRECT IMPACT WILL RESULT
<u>UNLIKELY</u>	TO HAVE ANY IMPACT

● PRIORITIES FOR FEDERAL AR&D FUNDING:

<u>VERY HIGH PRIORITY</u>	MUST BE FUNDED, REGARDLESS OF TOTAL BUDGET AVAILABLE
<u>HIGH PRIORITY</u>	SHOULD BE FUNDED IF POSSIBLE
<u>MEDIUM PRIORITY</u>	FUND IF ADEQUATE FUNDS EXIST
<u>LOW PRIORITY</u>	FUND ONLY UNDER HIGHEST BUDGET
<u>VERY LOW PRIORITY</u>	SHOULD NOT BE FUNDED

Example

III-V COMPOUND SEMICONDUCTOR MATERIALS FOR HIGH EFFICIENCY PHOTOVOLTAIC CELLS

THIS INCLUDES STUDIES OF NUCLEATION AND GROWTH, DOPANT INCORPORATION, DEFECT DENSITY REDUCTION, LATTICE MISMATCHED GROWTHS, STRESSED LAYERS AND SUBSTRATE DEVELOPMENT. MATERIALS SHOULD INCLUDE BINARY, TERNARY, AND QUATERNARY III-V COMPOUNDS, THIN POLYCRYSTALLINE FILMS AND THIN FILMS ON REUSABLE OR SACRIFICIAL SUBSTRATES.

CONTRIBUTION TO BASIC SCIENTIFIC UNDERSTANDING	VERY LIKELY		LIKELY		NOT LIKELY	
POTENTIAL IMPACT ON FURTHER TECHNOLOGY DEVELOPMENT BY PRIVATE INDUSTRY	EXCELLENT		PROBABLE		UNLIKELY	
PRIORITY FOR FEDERAL AR&D	ERY HIGH	HIGH	MEDIUM	LOW	LOWEST	

COMMENTS:

Evaluation Summary

- 62 RESPONSES WERE RECEIVED FROM PV EXPERTS IN INDUSTRY, UNIVERSITIES AND GOVERNMENT:
 - 29 INDUSTRY
 - 9 UNIVERSITY
 - 24 GOVERNMENT
- NORMALIZED SCORES WERE CALCULATED BY ASSIGNING VALUES TO QUALITATIVE RATINGS; AREAS WERE RANK-ORDERED FOR EACH EVALUATION CRITERION
- FOLLOWING CHARTS SHOW RANKINGS (1ST THROUGH 35TH) OF AR&D AREAS FOR THE THREE EVALUATION CRITERIA

Amorphous Silicon

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
LIGHT INDUCED CHANGES IN AMORPHOUS SILICON AND EFFECTS ON SOLAR CELL STABILITY	1	2-3	1
INTERFACE PROBLEMS ASSOCIATED WITH AMORPHOUS SILICON PHOTOVOLTAIC DEVICES	11-12	2-3	4
DEPOSITION METHODS FOR AMORPHOUS FILMS	11-12	1	2
MATERIAL CHARACTERIZATION AND THEORETICAL UNDERSTANDING OF THIN FILM AMORPHOUS MATERIALS	2	7	3
NEW AMORPHOUS MATERIALS	8-9	9-10	15

Concentrator Cells

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
CONCENTRATOR CELL OPTIMIZATION	28	21	20

PLENARY SESSION: T. SUREK

Crystalline Silicon

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
DEFECT PASSIVATION AND MATERIALS MODIFICATION FOR POLYCRYSTALLINE SILICON	10	8	12
BASIC MECHANISMS IN POLYCRYSTALLINE SILICON	6	15-16	10-11
CELL PHYSICS IN CRYSTALLINE SILICON	15-17	15-16	14
SILICON SOURCE MATERIAL RESEARCH	29	17-18	22
SILICON MATERIAL GROWTH	21	4	18-19

High Efficiency: III-V and Related Areas

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
III-V COMPOUND SEMICONDUCTOR MATERIALS FOR HIGH EFFICIENCY PHOTOVOLTAIC CELLS	4	12	6-7
FUNDAMENTAL STUDIES IN III-V COMPOUND SEMICONDUCTOR MATERIALS AND SOLAR CELLS	3	19	10-11
STRUCTURAL ELEMENTS OF HIGH EFFICIENCY PHOTOVOLTAIC CELLS	15-17	6	5

Innovative Concepts

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
NEW CONCEPTS	14	13-14	8
ORGANIC MATERIALS AND DEVICES	13	29	30

PLENARY SESSION: T. SUREK

Luminescent Concentrators

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
PHOTOCHEMICAL RESEARCH ON LUMINESCENCE IN SOLIDS	19	33-34	31-32
LUMINESCENT CONCENTRATORS	27	33-34	31-32

Photoelectrochemical Areas

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
FUNDAMENTAL PHOTOELECTROCHEMICAL PROCESSES	8-9	30-31	26-27
POLYCRYSTALLINE THIN FILMS FOR PHOTOELECTRO- CHEMICAL SOLAR CELLS	22-23	28	28
PHOTOELECTROCHEMICAL CELL STABILITY	20	30-31	26-27
OTHER RESEARCH IN PHOTOELECTROCHEMICAL CELLS	26	32	34
PHOTOELECTROCHEMICAL STORAGE	18	24-25	21

Support Research

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
ENCAPSULANT RESEARCH	24	9-10	16-17
INSULATION RESOURCE ASSESSMENT	30	24-25	24
MEASUREMENTS AND CHARACTERIZATION	25	5	6-7
METALLIZATION RESEARCH	22-23	17-18	16-17

PLENARY SESSION: T. SUREK

Systems and Modules

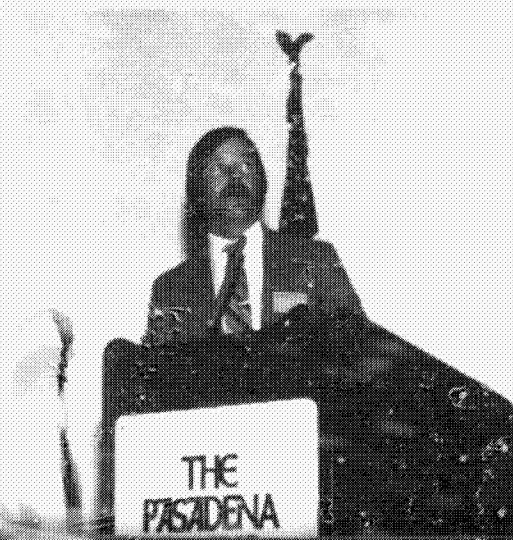
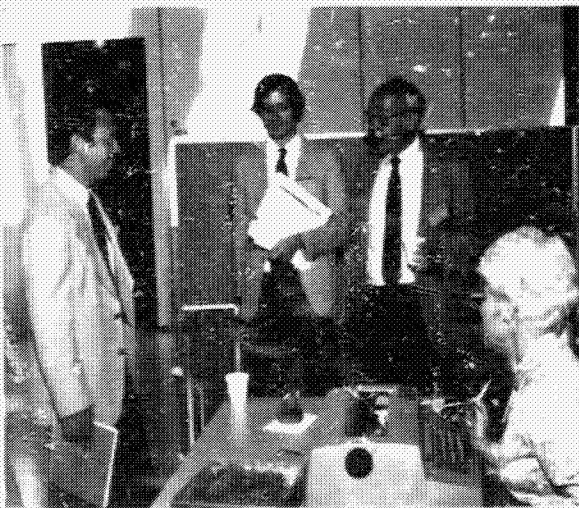
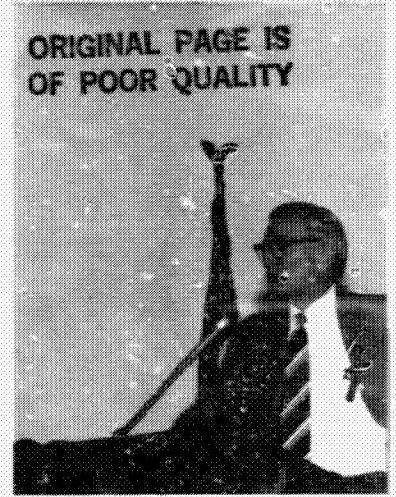
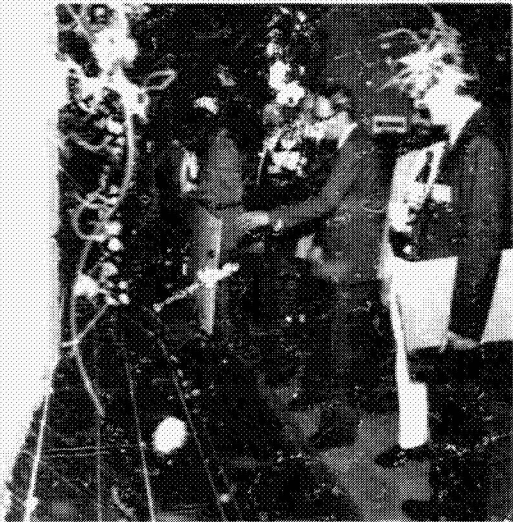
	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
FLAT PLATE MODULE RESEARCH	34	13-14	23
CONCENTRATOR MODULE RESEARCH	33	23	25
ADVANCED PHOTOVOLTAIC SYSTEMS RESEARCH	32	22	29
FRESNEL LENS RESEARCH	35	27	33

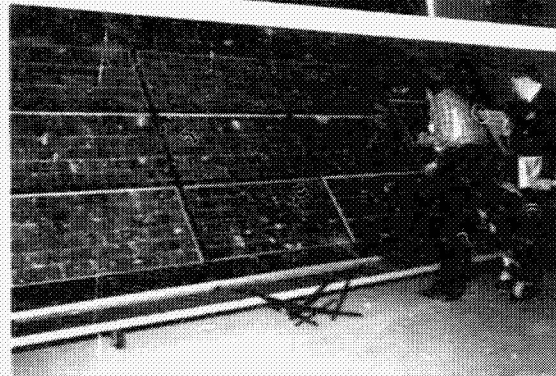
II - VI and Related Areas

	<u>SCIENTIFIC VALUE</u>	<u>TECHNOLOGY IMPACT</u>	<u>FUNDING PRIORITY</u>
RESEARCH ON COPPER INDIUM DISSELENIDE (CuInSe ₂) CELL STRUCTURES AND FABRICATION	15-17	11	9
BASIC STUDIES IN COPPER INDIUM DISSELENIDE (CuInSe ₂)	5	20	13
CONTINUED RESEARCH ON CdS/Cu ₂ S	31	35	35
ALTERNATE POLYCRYSTALLINE THIN FILM PHOTOVOLTAIC MATERIALS	7	26	18-19

Conclusions

- RANKINGS WERE GENERALLY CONSISTENT AMONG THE THREE GROUPS OF RESPONDEES
- "CONTRIBUTION TO BASIC SCIENTIFIC UNDERSTANDING" WAS RATED HIGHEST IN HIGH-RISK AREAS
- "POTENTIAL IMPACT ON FURTHER TECHNOLOGY DEVELOPMENT BY PRIVATE INDUSTRY" WAS ASSOCIATED WITH NEAR-TERM TECHNOLOGIES
- "PRIORITIES FOR FEDERAL AR&D FUNDING" WERE HIGHEST IN AREAS NOT WIDELY ADDRESSED BY INDUSTRY
- COPIES OF EVALUATION RESULTS ARE AVAILABLE ON REQUEST





ORIGINAL PAGE IS
OF POOR QUALITY



Technology Sessions

FLAT-PLATE COLLECTOR RESEARCH AREA

Silicon Material Task

R. Lutwack, Chairman

Reports of progress in research on processes for making silicon (Si) and in supporting studies were presented by three contractors and JPL.

Union Carbide Corp. reviewed its research on silane decomposition in a fluidized-bed reactor (FBR) process development unit (PDU) to make semiconductor-grade Si. The PDU, reactivated in late 1981 after having been shut down in May 1981 because of funding recisions, was modified by installation of a new heating system to provide the required temperature profile and better control, and testing was resumed. In one test, at 6.3% silane concentration, 100% conversion to Si was achieved.

Solarelectronics, Inc., reported on its investigation of a process for making trichlorosilane by the hydrochlorination of metallurgical-grade Si and silicon tetrachloride. Fabrication and installation of the test system employing a new 2-in.-dia reactor was completed, and tests were conducted to compare reactor performance with that of the earlier 1-in.-dia reactor. Good agreement was obtained. A corrosion test was also carried out on various candidate materials of construction for the reactor. All samples tested showed a weight gain, attributed to formation of metal silicide films that prevent further corrosion.

Hemlock Semiconductor Corp. described progress in the program to develop a process that converts trichlorosilane to dichlorosilane (DCS), which is reduced by hydrogen to make Si by a chemical vapor deposition step in a Siemens-type reactor. Testing of the DCS PDU integrated with Si deposition reactors continued, and semiconductor-grade Si is being made. It was found that hydrogen chloride can be used after a deposition run to remove selectively the Si deposited on the inside surfaces of the reactor bell jar, thereby preventing deposit build-up and bell-jar breakage.

In the JPL in-house program on conversion of silane to Si in an FBR, experiments in a 2-in.-dia reactor to define the operating window and to investigate the Si deposition kinetics were completed. Even with silane concentration as high as 65% in hydrogen, excessive formation of Si fines as well as bed agglomeration can be prevented by proper choice of operating conditions.

SILANE-TO-SILICON PROCESS

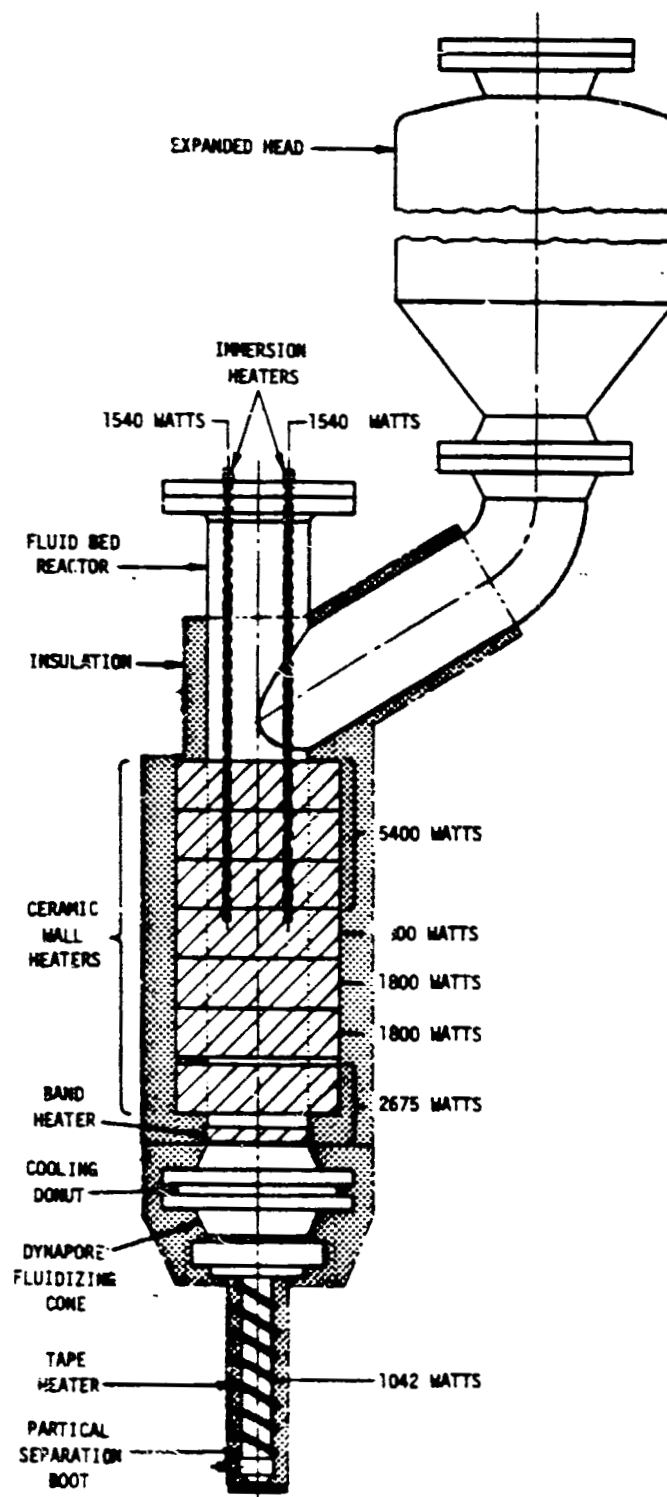
UNION CARBIDE CORP.

TECHNOLOGY POLYCRYSTALLINE SILICON R&D	REPORT DATE APRIL 22, 1982
APPROACH SILANE DECOMPOSITION IN A FLUID BED REACTOR TO MAKE SEMICONDUCTOR- GRADE POLYSILICON	STATUS <ul style="list-style-type: none">• FLUID BED REACTOR PDU WAS MODIFIED WITH A NEW HEATING SYSTEM• PDU IS OPERATIONAL & EXPERIMENTS ARE IN PROGRESS
CONTRACTOR UNION CARBIDE CORPORATION	
GOALS <ul style="list-style-type: none">• INVESTIGATE PROCESS FEASIBILITY• DETERMINE OPERATING WINDOW• DEMONSTRATE STEADY STATE OPERATION• DEMONSTRATE SILICON PURITY FOR PV APPLICATION	

Fluid-Bed Silane Decomposition R&D Summary

- 6 - INCH DIAMETER FLUID BED PDU WAS ASSEMBLED & STARTED UP IN EARLY 1981
UNDER PREVIOUS CONTACT-PHASE
- R & D WORK WAS TEMPORARILY SUSPENDED & REACTIVATED IN 4th Q 1981
- PDU MODIFICATIONS INVOLVING INSTALLATION OF A NEW HEATING SYSTEM
WERE COMPLETED
- FLUIDIZATION & BED HEATING TESTS IN HYDROGEN ATMOSPHERE
WERE CONDUCTED
- PDU WAS RESTARTED WITH SILANE & 3 EXPERIMENTAL RUNS HAVE BEEN CONDUCTED

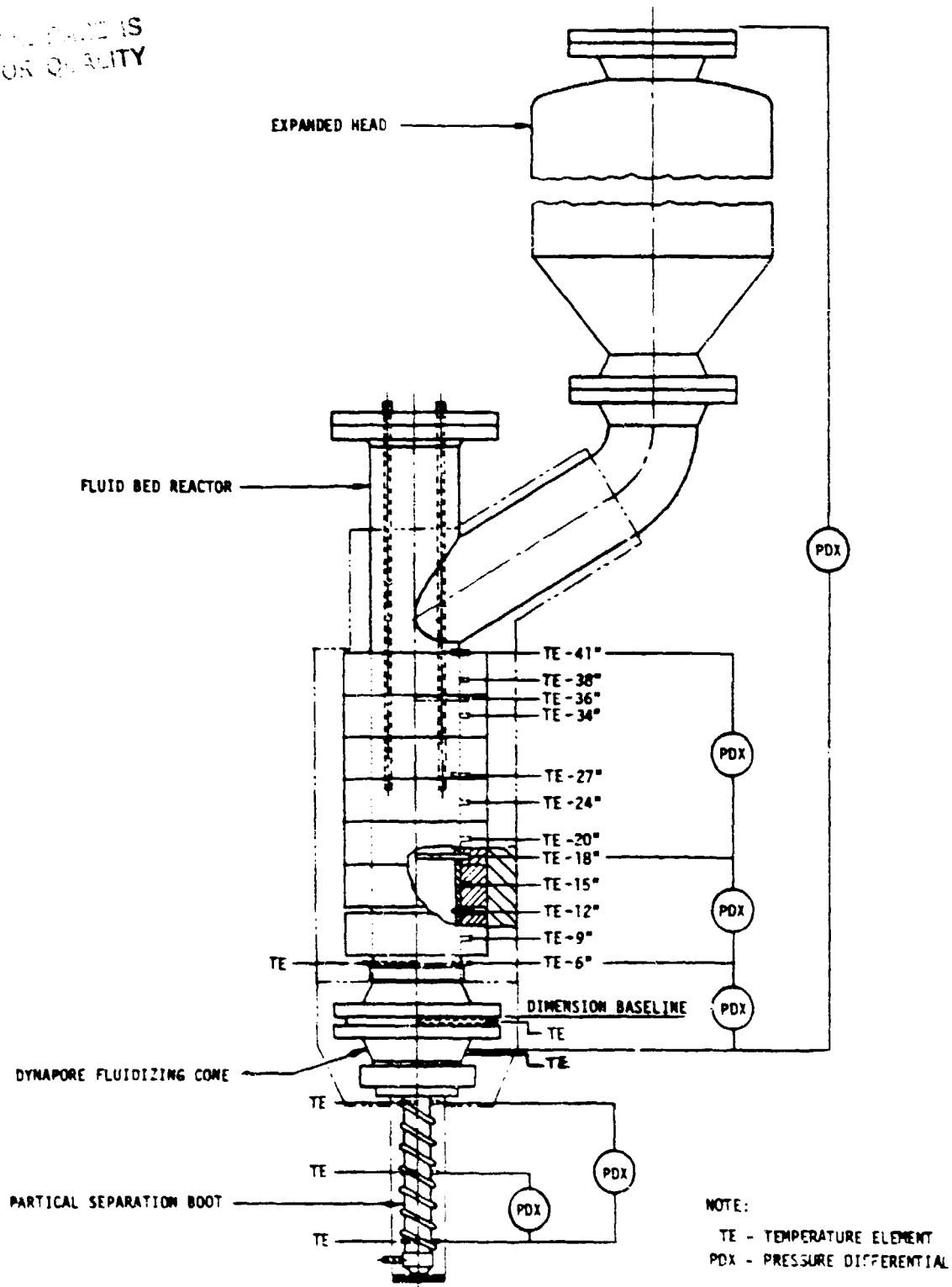
Fluid-Bed Reactor Heating System



SILICON MATERIAL TASK

FBR Temperature & Pressure Tap Locations

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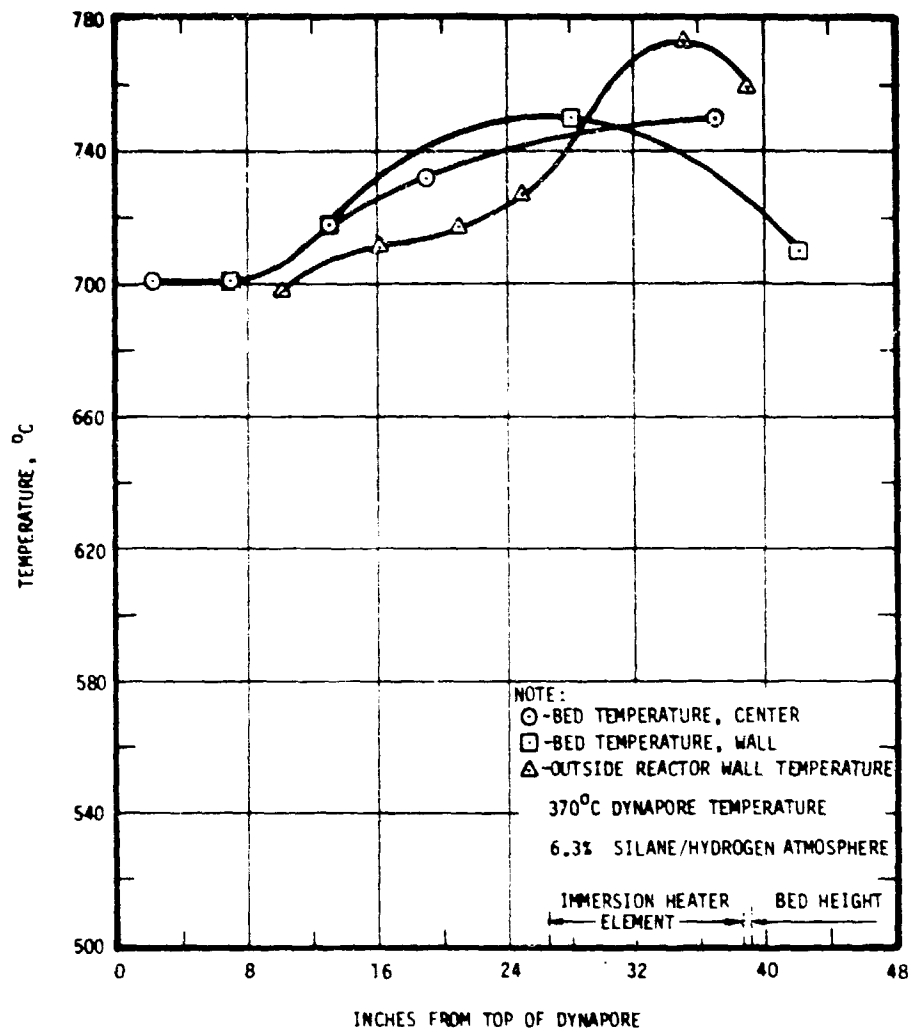
SILICON MATERIAL TASK

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FBR Run Summary

RUN NO.	SILANE FEED DURATION HRS.	MAXIMUM SILANE IN FEED, %	SILANE CONVERSION, %	BED TEMP., °C	DISTRIBUTOR TEMP., °C	U/UMF	COMMENTS
1	4.5	6.3	100	700-730	340-375	5.5	<ul style="list-style-type: none"> ● COMPLETE CONVERSION ● GRADUAL INCREASE OF ΔP ACROSS DISTRIBUTOR
2	2.0	18.6	99.2	500-645	300-335	3.5	<ul style="list-style-type: none"> ● GOOD CONVERSION WITH HIGH SILANE FEED CONCENTRATION ● PARTIAL PLUGGING OF DISTRIBUTOR AT THE END OF RUNS 1 & 2
3	3.0	12.0	<90	500-560	310-325	6	<ul style="list-style-type: none"> ● INCOMPLETE CONVERSION SINCE BED TEMP. WAS LOW. ● DISTRIBUTOR ΔP CONSTANT ● PRODUCT WITHDRAWAL & SEED INJECTION TESTED

FBR Test Temperature Profile



Problems and Concerns

- GAS DISTRIBUTOR OVER-HEATING & PLUGGING
- AGGLOMERATION OF SILICON PARTICLES IN FLUID BED REACTOR
- INSUFFICIENT BED HEIGHT IN THE CURRENT PDU
- POSSIBLE SILICON CONTAMINATION DUE TO IMPURE FEED/IMPROPER MATERIALS

SILICON MATERIAL TASK

Plans

- **FINISH CURRENT EXPERIMENTS TO DETERMINE OPERATING WINDOW.**
- **CONDUCT LONG RUN TO INVESTIGATE STEADY STATE OPERATION.**
- **EVALUATE PARTICLE GROWTH RATE & MORPHOLOGY.**
- **PROVIDE SAMPLES TO JPL FOR ANALYSIS.**

HYDROCHLORINATION PROCESS

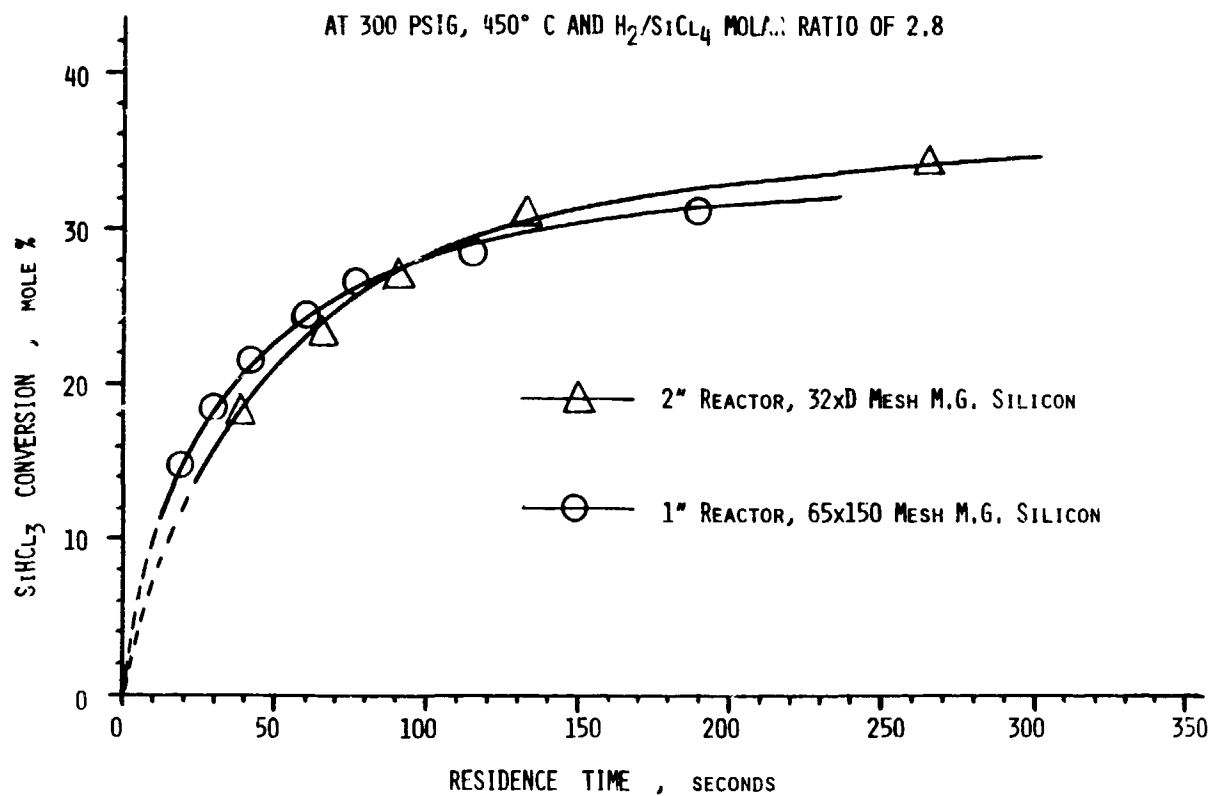
SOLARELECTRONICS, INC.

TECHNOLOGY POLYCRYSTALLINE SILICON METAL	REPORT DATE APRIL 22, 1982. 20TH PIM
APPROACH HYDROCHLORINATION OF METALLURGICAL GRADE SILICON TOGETHER WITH SILICON TETRACHLORIDE AND HYDROGEN TO FORM TRICHLOROSILANE FOR PRODUCING SILICON METAL CONTRACTOR SOLARELECTRONICS, INC.	STATUS JPL CONTRACT NO. 956061 (JULY 9, 1981 - JULY 8, 1982.) $3 \text{ SiCl}_4 + 2 \text{ H}_2 + \text{Si} = 4 \text{ SiHCl}_3$ <ul style="list-style-type: none"> ● NEW TWO INCH REACTOR OPERATIVE; RESULTS CHECKED OUT WITH PREVIOUS EXPERIMENTS ● EFFECT OF PRESSURE: HIGHER PRESSURE GIVES A HIGHER SiHCl_3 CONVERSION BUT AT A SLOWER REACTION RATE ● HCL ANALYSIS: 0.1 - 0.5% HCL PRESENT ● CORROSION TESTS: CARBON STEEL, NICKEL, COPPER, STAINLESS STEEL, INCOLOY 800H, HASTELLOY B-2 ● CORROSION MECHANISM STUDY: THE NATURE OF THE SILICIDE PROTECTIVE FILM, ELEMENTAL ANALYSIS, SEM ANALYSIS ● MILESTONE CHECK POINT, PROGRAM REVIEW, REVISED PROGRAM PLAN.
GOALS TO CARRY OUT A BASIC RESEARCH PROGRAM ON THE HYDROCHLORINATION REACTION OF SiCl_4 , <ul style="list-style-type: none"> ● REACTION KINETICS MEASUREMENTS: AS A FUNCTION OF T, P AND C ● EFFECT OF PRESSURE ● REACTION MECHANISM: STEP-WISE REACTION, INTERMEDIATE AND BY-PRODUCT ● CORROSION MECHANISM OF METALS AND ALLOYS IN THE HYDROCHLORINATION REACTION ENVIRONMENT. 	

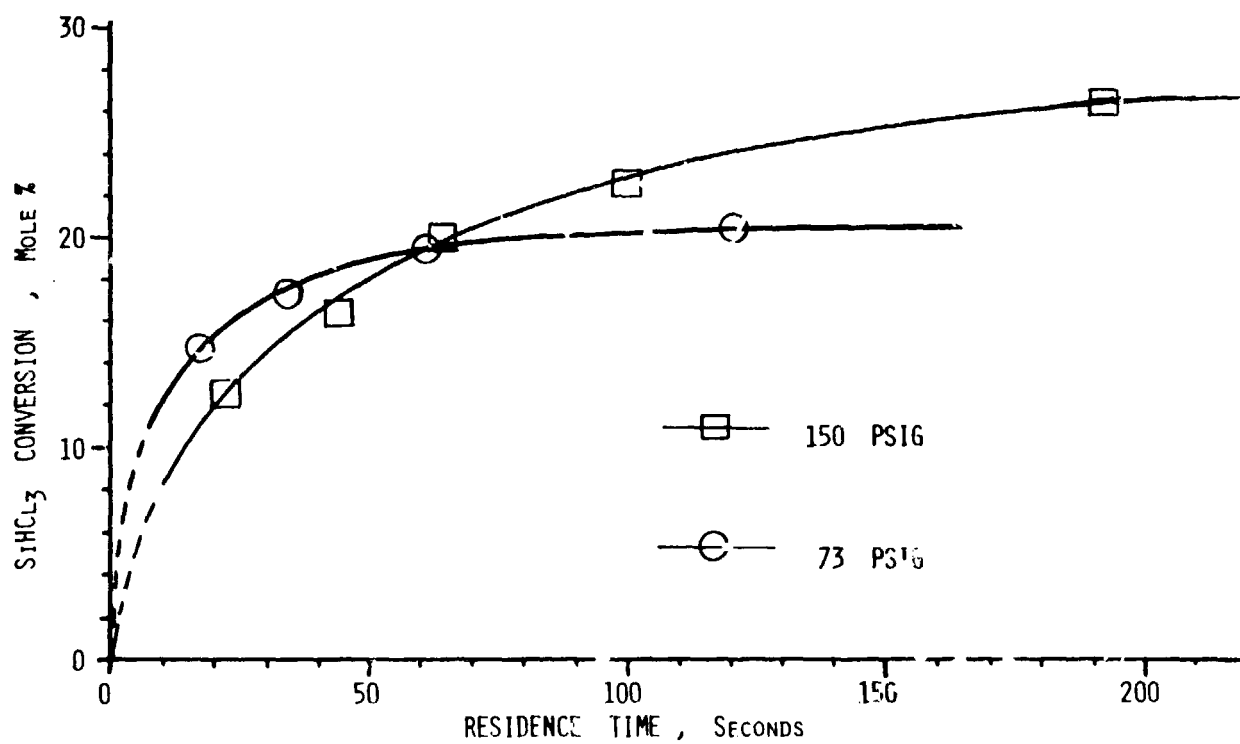
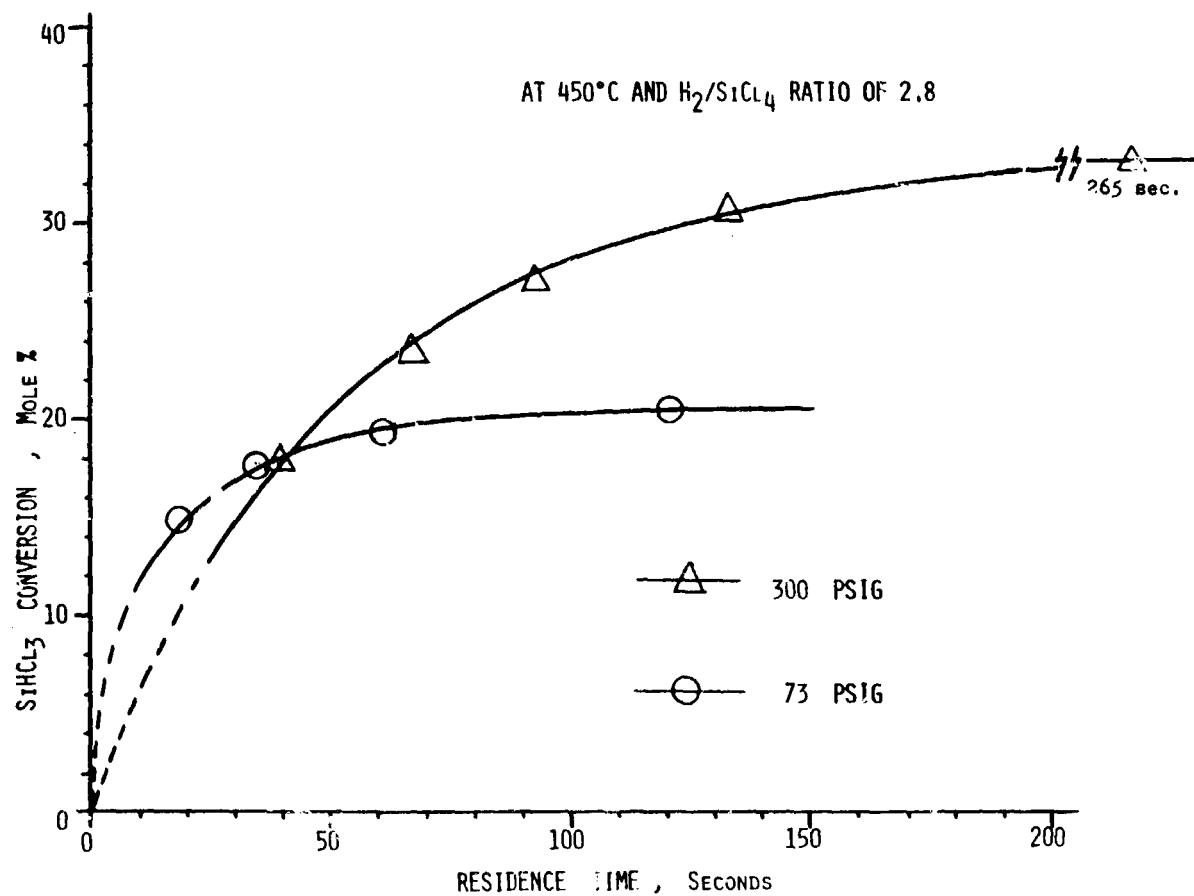
SILICON MATERIAL TASK

Hydrochlorination of SiCl_4 and mgSi to SiHCl_3

AT 300 PSIG, 450° C AND H_2/SiCl_4 MOLAL RATIO OF 2.8



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Effect of Pressure on Hydrochlorination of SiCl_4 and mgSi 

SILICON MATERIAL TASK

HCl Analysis in the Hydrochlorination of SiCl_4

AT 500°C, 300 PSIG AND H_2/SiCl_4 RATIO OF 2.0

SAMPLE NO.	RESIDENCE TIME SECOND	REACTION PRODUCT COMPOSITION, AREA%			
		HCL	SiH_2Cl_2	SiHCl_3	SiCl_4
A	207	0.5970	0.7512	32.66	64.04
B	207	0.5875	0.7611	31.64	66.65
1	96	0.1235	0.4878	26.69	71.98
2	96	0.1388	0.5163	26.75	71.92
3	138	0.3326	0.7961	31.75	66.57
4	138	0.4343	0.3325	31.84	66.80
5	207	0.5962	0.7303	31.95	65.82
6	207	0.5735	0.8337	31.93	66.05

Corrosion Tests on Metals and Alloys

(87 HOURS @ 500°C, 300 PSIG, $\text{H}_2/\text{SiCl}_4 = 2.0$)

METALS, ALLOY	APPROXIMATE COMPOSITION
CARBON STEEL	BASICALLY IRON, + 95% FE
NICKEL	PURE
COPPER	PURE
STAINLESS STEEL (TYPE 304)	68% FE, 19% CR, 10% NI, 2% MN, 1% SI
ALLOY 400 (MONEL)	2/3 NICKEL, 1/3 COPPER
INCOLOY 800H	45% FE, 30% NI, 23% CR, 1% MN, 0.6% SI
HASTELLOY B-2	68% NI, 28% MO, 2% FE, 1% CR, 1% MN

SILICON MATERIAL TASK

Corrosion Test on Pure Nickel, 87 Hours

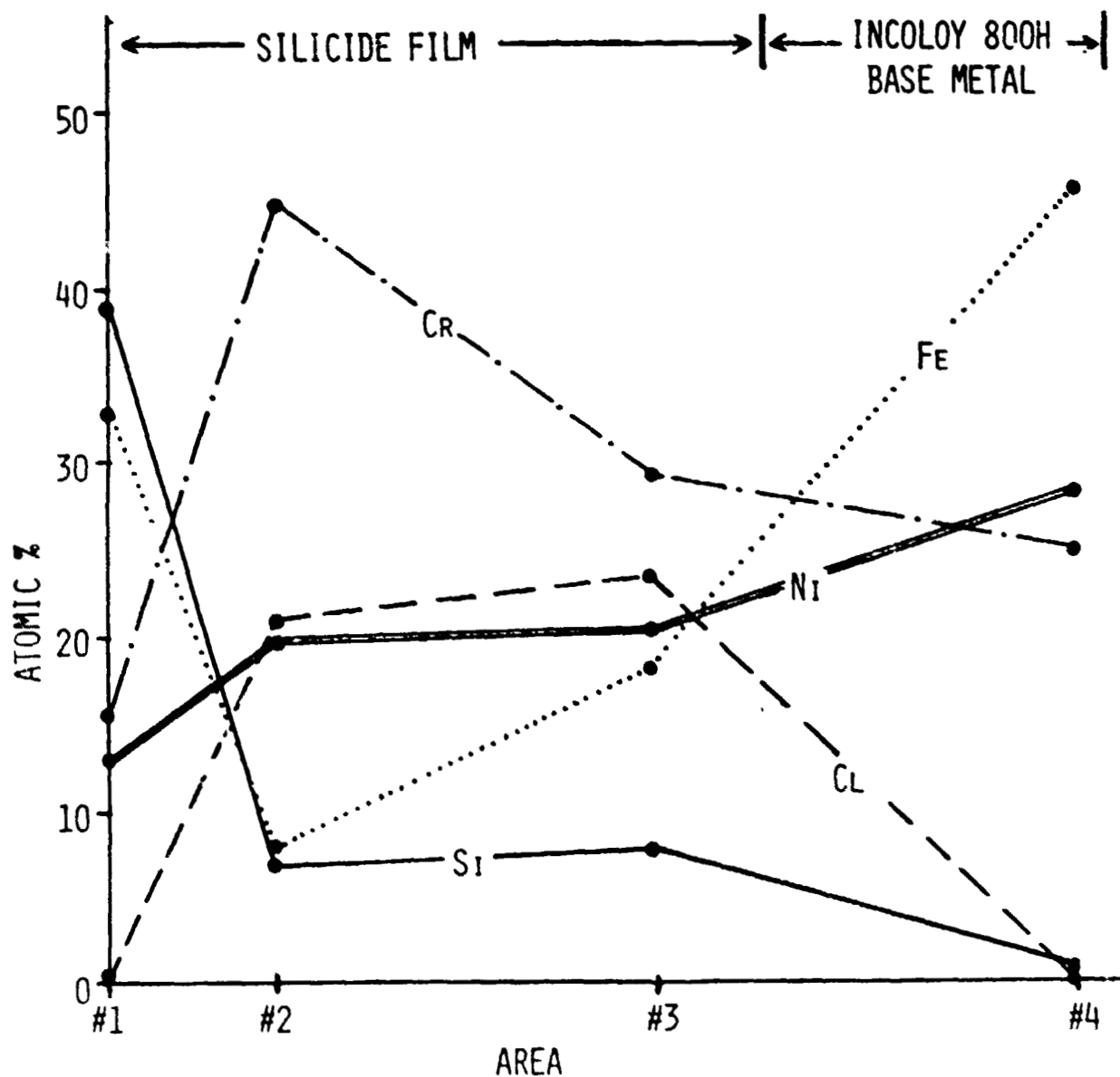
AT 500°C, 300 PSIG AND $H_2/SiCl_4$ OF 2.0

SAMPLE NO.	DISTANCE* FROM GRID PLATE INCH	TOTAL SURFACE AREA CM ²	WEIGH BEFORE REACTION G.	WEIGH AFTER REACTION G.	WEIGH GAIN M.G.	WEIGH GAIN PER UNIT AREA M.G./CM ²
1	31.3	20.4	4.8807	4.9017	21.2	1.04
2	28.0	20.7	4.9450	4.9676	22.6	1.09
3	23.2	19.7	4.7197	4.7576	37.9	1.92
4	20.0	20.8	4.9888	5.0921	103.3	4.97
5	16.2	20.3	4.8710	5.0639	192.9	9.50
6	13.0	20.4	4.8850	5.1481	261.3	12.8
7	9.5	20.8	4.9808	5.3098	329.0	15.8
8	6.2	20.3	4.8638	5.2190	355.2	17.5
9	2.5	20.8	4.9680	5.2502	282.2	13.6

- THE SILICON METAL BED IS ABOUT 18 INCHES HIGH.

NOTE: UNLIKE INCOLOY 800H AND STAINLESS STEEL, THE SILICIDE FILM ON PURE NICKEL IS NOT REACTIVE TOWARD AIR AND MOISTURE

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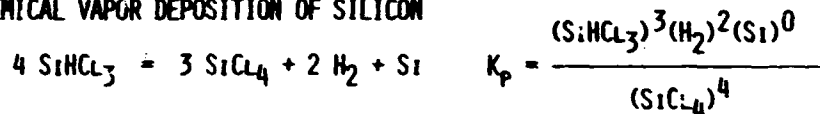


Corrosion Test on Incoley 800H: 238 h at 500°C, 300 osig, $H_2/SiCl_4 = 2$
SEM Analysis of Cross-Sectional Area

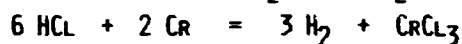
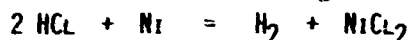
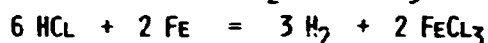
Corrosion Mechanism Study

FORMATION OF THE SILICIDE PROTECTIVE FILM: CHEMICAL REACTIONS

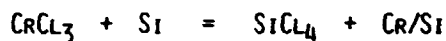
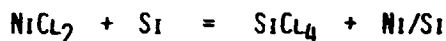
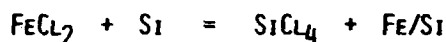
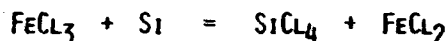
(1) CHEMICAL VAPOR DEPOSITION OF SILICON



(2) REACTION WITH HCL

VAPOR PRESSURE
OF METAL CHLORIDE

(3) REACTION OF METAL CHLORIDE WITH SILICON



SILICIDE FILM

A STEADY STATE EQUILIBRIUM ?

QUESTION: INCOLOY 800H, 87 HOURS = 1.78 M.G./CM², 238 HOURS = 2.71 M.G./CM²

FORMATION OF THE SILICIDE PROTECTIVE FILM: PHYSICAL PROCESS

(1) MELTING POINTS OF THE BASE METAL

Cu = 1083°, Mn = 1260°, Si = 1420°, Ni = 1455°, Fe = 1535°,

Cr = 1890°, Mo = 2620°

(2) METAL-SILICON PHASES (SILICIDES)

Cu₃Si 558°, 802°Ni₃Si₂ 845°, 964°; NiSi 992°Cu₃Ni 1185°Fe₅Si₃ 825°, 1030°; FeSi₂ 1220°Mn₃Si 1075°; MnSi 1275°CrSi₂ 1550°; CrSi 1600°MoSi₂ 1870°; Mo₃Si₂ 2190°

VERSUS REACTION

TEMPERATURE = 500°

CR, MO SILICIDES ARE FORMED AT HIGHER TEMPERATURES THAN THOSE OF CU, NI. THIS MAY EXPLAIN THE LARGE DIFFERENCES ON THE AMOUNT OF SI DEPOSITED ON THE TEST SAMPLES.

Corrosion Test Results: Weight Gain by Test Samples

(87 HOURS AT 500°C, 300 PSIG, $H_2/SiCl_4 = 2.0$)

TEST SAMPLES, ALLOYS	TOTAL SURFACE AREA CM ²	WEIGH BEFORE REACTION G.	WEIGH AFTER REACTION G.	WEIGH GAIN M.G.	WEIGH GAIN PER UNIT AREA M.G./CM ²
CARBON STEEL	15.6	3.6100	3.7435	133.5	8.56
PURE NICKEL	20.8	4.9808	5.3098	329.0	15.8
PURE COPPER	23.1	8.2623	8.5986	336.3	14.6
ALLOY 400 (MONEL)	31.2	21.3429	21.4448	101.9	3.27
S.S. (TYPE 304)	20.0	12.2397	12.2972	57.5	2.88
INCOLOY 800H	28.7	13.4049	13.4561	51.2	1.78
HASTELLOY B-2	32.2	23.1987	23.2417	43.0	1.34

QUESTION: WILL THE SILICIDE FILM CONTINUE TO GROW ?

Corrosion Mechanism Study

IS THERE ANY CORROSION ?

(1) THE SILICIDE PROTECTIVE FILM

- ALL TEST SAMPLES SHOW A WEIGH GAIN
- A SILICIDE FILM IS FORMED ON THE SURFACE OF ALL TEST SAMPLES
- NO SIGNIFICANT CORROSION IS EXPECTED WITH A STABLE SILICIDE PROTECTIVE FILM

(2) SCALING: UNLIMITED GROWTH OF THE SILICIDE FILM

- A THICK SILICIDE SCALE CAN WEAKEN THE REACTOR WALL DUE TO THE POOR MECHANICAL PROPERTY OF SILICIDES
- A THICK SILICIDE SCALE CAN BE BROKEN OFF DUE TO MECHANICAL AND THERMAL STRESS - EROSION BY SCALING

CASE I NICKEL: 110 MICRONS FILM AFTER 87 HOURS, CA. 50% NICKEL

$$\frac{0.5 \times 365 \times 24 \times 110 \times 10^{-4}}{87 \times 2.54 \times 10^{-3}} = 218 \text{ MILS/YEAR}$$

CASE II INCOLOY 800H: 238 HOURS, SILICIDE FILM WITH 8.6 MICRON BASE METAL

$$\frac{365 \times 24 \times 8.6 \times 10^{-4}}{238 \times 2.54 \times 10^{-3}} = 12 \text{ MILS/YEAR}$$

SILICON MATERIAL TASK

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CONCLUSION:

(1) MECHANISM

- CHEMICAL VAPOR DEPOSITION OF Si
- ↳ INTERACTION OF Si WITH BASE METALS - CHEMICAL PROCESS
- INTERACTION OF Si WITH BASE METALS - PHYSICAL PROCESS
- DEVELOPMENT OF METAL-SILICON PHASES
- FORMATION OF THE SILICIDE FILM OF COMPLEX COMPOSITION
- ALLOYS WITH HIGH Ni , Cr , Mo CONTENTS DESIRABLE

(2) FURTHER EXPERIMENTAL STUDIES RECOMMENDED

- TIME DEPENDENCY: GROWTH OF THE SILICIDE FILM AS A FUNCTION OF TIME, LIMITED OR UNLIMITED GROWTH,
- GROWTH OF THE SILICIDE FILM AS A FUNCTION OF TEMPERATURE - ACCELERATED TEST AT HIGHER TEMPERATURES, UPPER TEMP. LIMIT,
- COMPOSITIONS OF THE BASE ALLOYS.

Other Forms of Corrosion to Consider

CORROSION MECHANISM OF METAL ALLOYS IS BY FAR A ELECTRO-CHEMICAL PROCESS IN THE PRESENCE OF A ELECTROLYTE, SUCH AS, WATER. IN THIS OXYGENATED ENVIRONMENT (ACID OR BASE), THE ALLOY RELIES ON A STABLE OXIDE FILM FOR PROTECTION. THE STABLE NICKEL AND CHROMIUM OXIDE FILM IS THE BASIS FOR THE CORROSION RESISTENCE OF MANY Ni , Cr BASED ALLOYS. STILL MORE STABLE OXIDE FILMS ARE THOSE OF TITANIUM, ZIRCONIUM AND TANTALUM. THE PROTECTIVE MECHANISM IS DIFFERENT FROM THAT OF THE SILICIDE PROTECTIVE FILM FORMED UNDER THE HYDROCHLORINATION REACTION ENVIRONMENT, WHICH DOES NOT APPEAR TO INVOLVE THE PRESENCE OF AN OXIDE FILM.

Potential Corrosions Other Than the Reaction Environment

- (1) MANUFACTURING PROCESS: METALLURGICAL HISTORY OF THE METAL ALLOY
- (2) FABRICATION: MECHANICAL AND THERMAL PROCESS (FORMING, WELDING, ETC.)
 "SENSITIZATION" OF AUSTENITIC STAINLESS STEEL: PRECIPITATION OF CHROMIUM CARBIDE ($Cr_{23}C_6$) AND DEPLETION OF CHROMIUM AT GRAIN BOUNDARY BY HEATING.
- (3) TESTING, STORAGE, TRANSPORTATION: CONTAMINATION
- (4) ATMOSPHERIC ENVIRONMENT: PLANT ENVIRONMENT IS CORROSIVE (HCl , CHLORIDE PRESENT)
 "CHLORIDE STRESS CORROSION CRACK" OF STAINLESS STEEL DUE TO INTERGRANULAR ATTACK BY CHLORIDE ACCELERATED BY INTERNAL STRESS (316L OR HIGH Ni)
- (5) HIGH TEMPERATURE ENVIRONMENT: OXIDATION, CHLORIDE, SULFUR (GAS-FIRED)
- (6) SERVICE, REPAIR: SILICIDE PROTECTIVE FILM IS REACTIVE TOWARD MOISTURE.

SILICON MATERIAL TASK

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Optimum Material of Construction for the Reactor

- (1) CARBON STEEL: POOR
 - POTENTIAL PROBLEMS: HYDROGEN EMBRITTLEMENT, SCALING
 - LOW CORROSION RESISTENCE IN GENERAL
 - LOWER COST
- (2) STAINLESS STEEL: GOOD
 - SATISFACTORY UNDER THE HYDROCHLORINATION REACTION ENVIRONMENT
 - GOOD CORROSION RESISTENCE IN GENERAL, CHLORIDE STRESS CORROSION CRACK
 - MEDIUM COST
- (3) HIGH NICKEL, CHROMIUM, MOLYBDENUM ALLOYS: BETTER
 - GOOD CORROSION RESISTENCE ALL-ROUND
 - HIGH CREEP RESISTENCE (STRENGTH AT HIGH TEMPERATURES)
 - HIGHER COST

ALLOYS	APPROXIMATE COMPOSITION							PRICE \$/LB.	PRICE RATIO CORRECTED FOR DESIGN STRENGTH
	Ni	Cr	Mo	Fe	Co	Mn	Si		
S.ST. (TYPE 316L)	12	17	2.5	66	-	1.5	0.5	2.09	1.00
INCOLOY 800H	31	22	-	45	-	1.0	0.6	-	-
HASTELLOY G	20	22	6	36	2.5	1.5	0.5	7.86	2.65
HAYNES ALLOY 625	62	22	9	5	1.0	0.5	0.5	11.37	3.11
HASTELLOY B-2	67	1	28	2	1.0	1.0	-	19.95	5.18

DICHLOROSILANE CVD PROCESS

HEMLOCK SEMICONDUCTOR CORP.

TECHNOLOGY POLYCRYSTALLINE SILICON	REPORT DATE APRIL, 1982
APPROACH CHEMICAL VAPOR DEPOSITION OF POLY-SILICON FROM DICHLOROSILANE (DCS) CONTRACTOR HEMLOCK SEMICONDUCTOR CORPORATION	STATUS <ul style="list-style-type: none">• 5" Ø REDISTRIBUTION REACTOR EVALUATION COMPLETED• CATALYST LIFE >90% ORIGINAL CAPACITY AFTER 2 MONTHS OPERATION AT CAPACITY• QUARTZ TUBE DEPOSITION REACTOR CONSTRUCTION COMPLETED• HCL ETCH LINES INSTALLED TO INTERMEDIATE REACTOR• MODEL 11D REACTOR STARTED UP AND EVALUATION IN PROGRESS• SILICON PURITY FROM REDISTRIBUTED TCS IS SEMICONDUCTOR GRADE QUALITY
GOALS <ul style="list-style-type: none">• ESTABLISH PROCESS FEASIBILITY THROUGH LABORATORY EXPERIMENTS AND COMPONENT TESTING• INVESTIGATE CRITICAL ELEMENTS OF PROCESS VIA OPERATION OF PROCESS DEVELOPMENT UNIT• POLYSILICON PRICE OF LESS THAN \$21/KG (1980 \$, 1000-MT/YR, 20% ROI) AND PURITY APPROACHING OR EQUALLING SEMICONDUCTOR-GRADE POLYSILICON	

Schedule of Effort by Phases

Oct. 1979		June 25, 1981												
Time (Mo.)	Project	3	6	9	12	15	18	21	24	27	30	33	36	39
Phase 1	Feasibility/EPSDU Preliminary Design													
Phase 2	Redistribution Rx and Decomposition Rx PDU Evaluation EPSDU Design (Deleted)													
Phase 3 (Curtailed)	EPSDU Detailed Design and Construction													

SILICON MATERIAL TASK

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Activities

- PDU START UP
- PDU CLEAN UP
- PDU START UP AND OPERATION
- EVALUATION OF 5" DIAMETER REDISTRIBUTION REACTOR
- QUARTZ TUBE DEPOSITION REACTOR CONSTRUCTED
- INTERMEDIATE REACTOR OPERATION USING DICHLOROSILANE
FEED STOCK WITH POST HCL ETCH
- POLYCRYSTALLINE SILICON PURITY EVALUATION
(BORON, DONOR, CARBON)
- START-UP OF MODEL 11D DICHLOROSILANE DECOMPOSITION
REACTOR
- SAMPLES OF DCS POLYSILICON SENT TO JPL AND
WESTINGHOUSE FOR EVALUATION

December Shutdown

Scheduled shutdown
before Christmas

Flush system with TCS

Purge out with Nitrogen

Pressure with Nitrogen

SILICON MATERIAL TASK

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Startup Problems

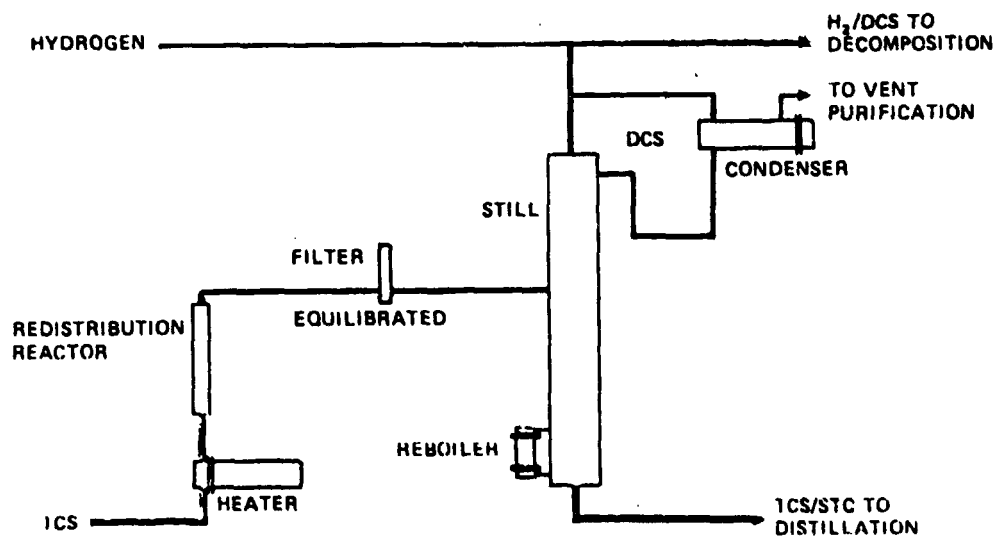
PROBLEM: Filter plugging

CAUSE: Catalyst support screen
separated from plate

ACTION: Redesign support plates
Dual filter system

**** MAJOR CLEAN UP EFFORT ****

DCS PDU Flow Diagram



SILICON MATERIAL TASK

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PDU Cleanup

PDU pressure checked &
purged out with nitrogen

Redistribution reactor repacked
with DOWEX

Steam tracing turned on column &
purged out with nitrogen

Moisture check showed no sign of water

PDU Startup Plan

Load in new DOWEX catalyst
3/9

Purge with hot nitrogen
3/9 to 3/10

Start-up
3/11

Safety review for Model 11 reactor
& updated SOP for PDU complete

SILICON MATERIAL TASK

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Si Production by DCS Decomposition

A. DICHLOROSILANE PRODUCTION

(CATALYZED REDISTRIBUTION OF TRICHLOROSILANE)



B. SILICON PRODUCTION

(DICHLOROSILANE DECOMPOSITION)



C. TRICHLOROSILANE PRODUCTION

(HYDROGENATION OF SILICON TETRACHLORIDE)



PDU Objectives

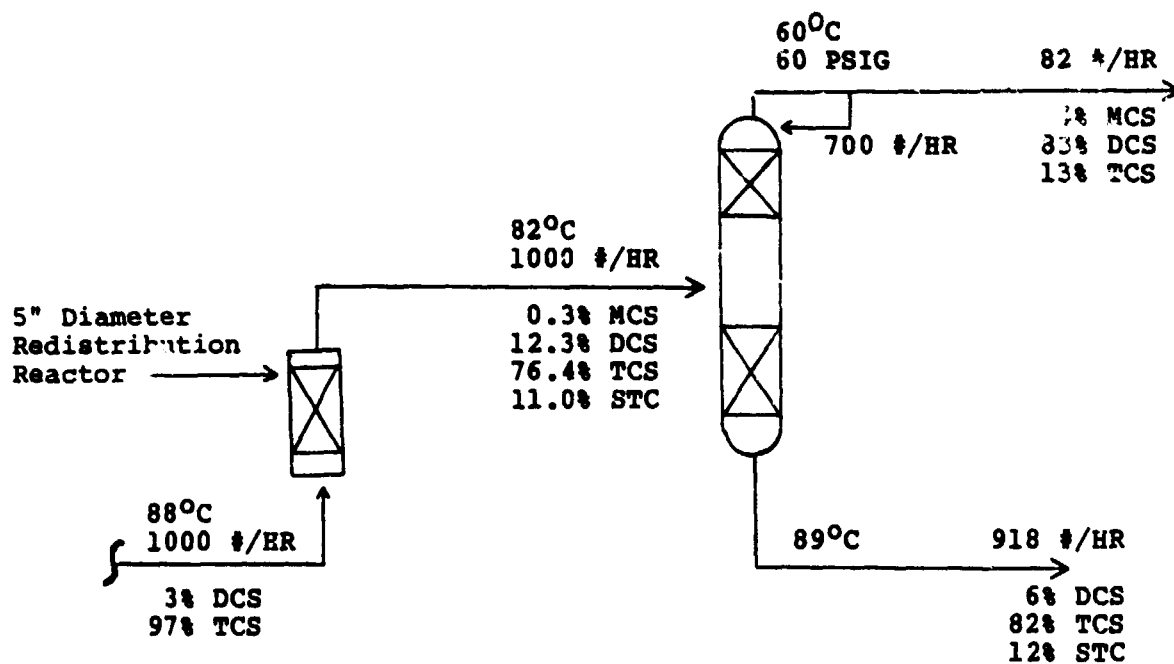
- DCS PRODUCTION 70 LB/HR
- REDISTRIBUTION CONVERSION >10%; DETERMINE TEMPERATURE AND RESIDENCE TIME TO ACHIEVE THIS
- PRESSURE DROP ΔP VS. VELOCITY IN CATALYST BED
- CATALYST LIFE >90% ORIGINAL CAPACITY AFTER 2 MONTHS OPERATION AT CAPACITY
- DETERMINE IF CATALYST MIGRATION OCCURS

SILICON MATERIAL TASK

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5-in.-Dia Redistribution Reactor

PDU Conditions at Capacity



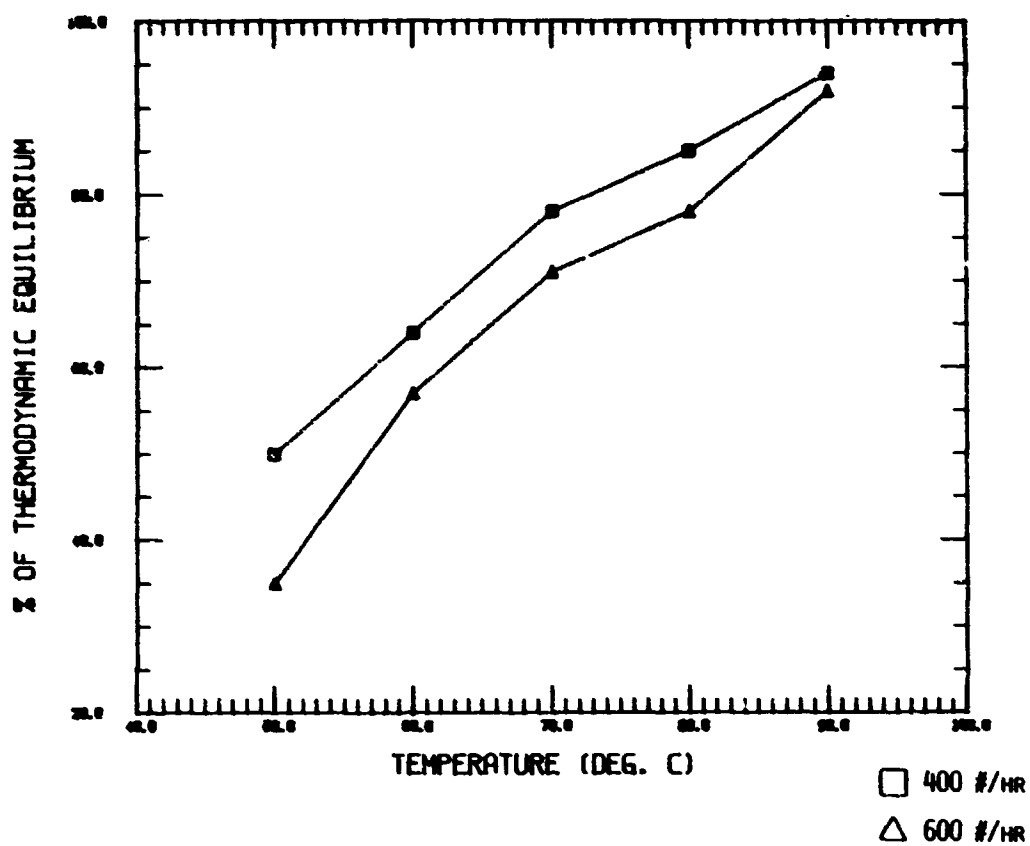
SILICON MATERIAL TASK

ORIGINAL PROBLEMS
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DCS Production From PDU

MONTH	# DCS PRODUCED	% ON-LINE TIME	REDISTRIBUTION REACTOR SIZE (Q)
JUNE	11.000	96	3"
JULY	7.000	36	3"
AUGUST	10.000	45	3"
SEPTEMBER	6.200	27	5"
OCTOBER	18.400	95	5"
NOVEMBER	14.350	70	5"
DECEMBER	16.000	66	5"
JANUARY	0	0	5"
FEBRUARY	0	0	5"
MARCH	7.840	46	5"

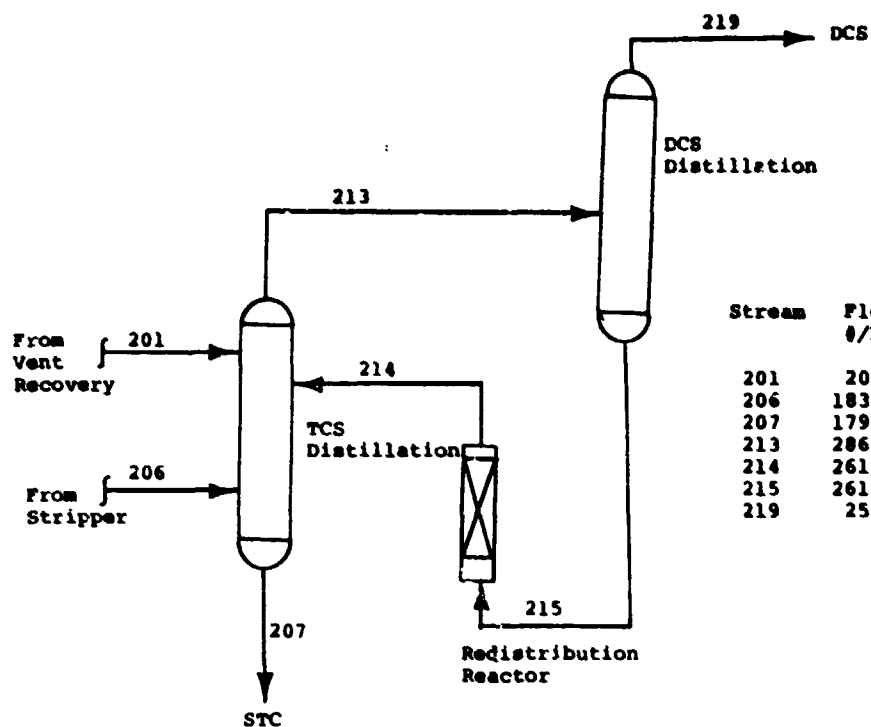
Kinetic Evaluation for 5-in. Redistribution Reactor



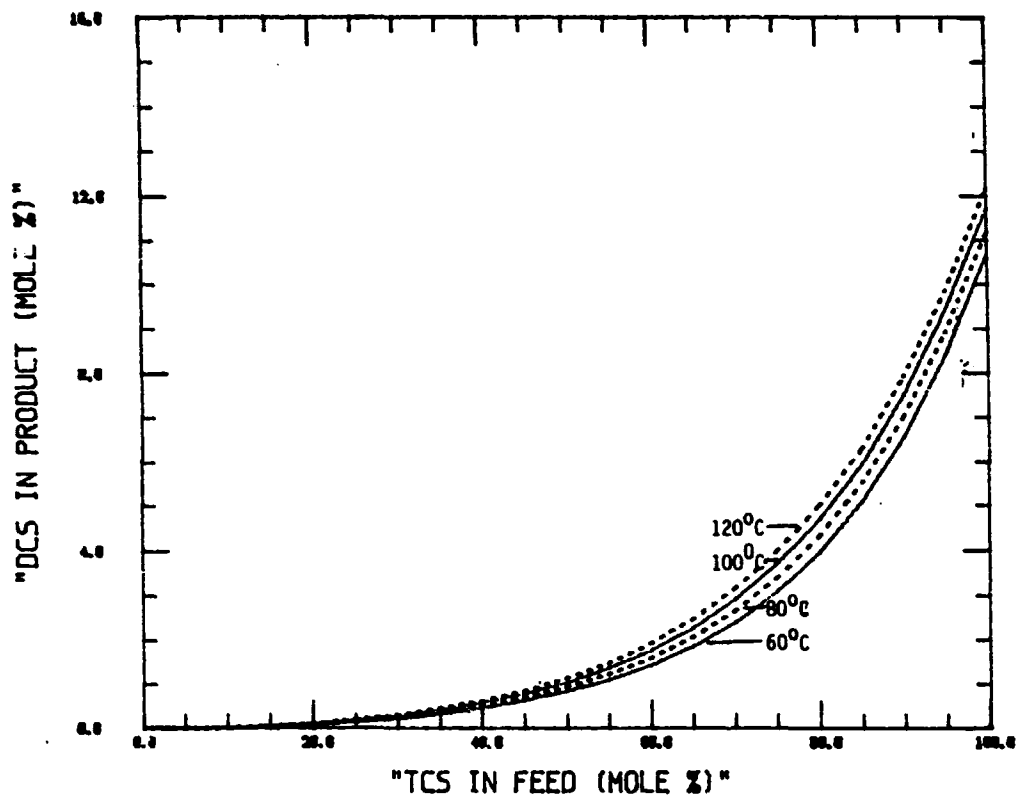
SILICON MATERIAL TASK

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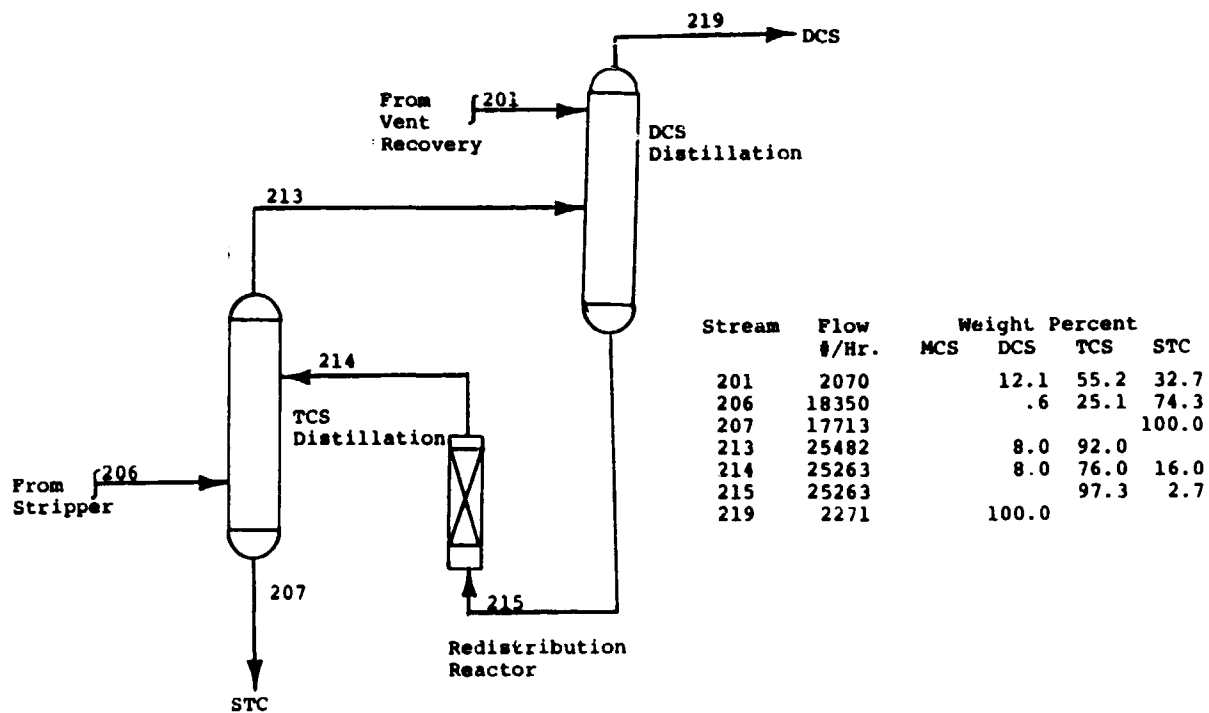
Redistribution Reactor at Bottom of DCS Column I



Stream	Flow #/Hr.	Weight Percent			
		MCS	DCS	TCS	STC
201	2070		12.1	55.2	32.7
206	18350		.6	25.1	74.3
207	17907				100.0
213	28656		8.7	91.3	
214	26153	.2	7.5	78.5	13.8
215	26153			100.0	
219	2508	2.8	91.5	5.7	

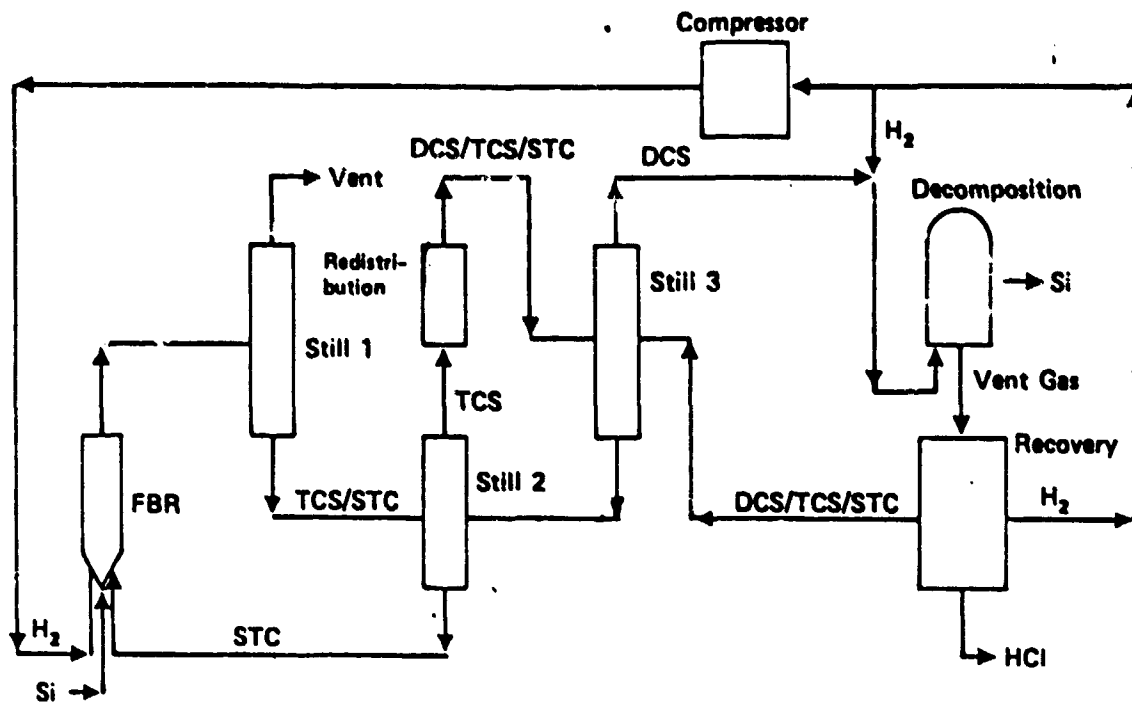
Thermodynamic Redistribution Data:
TCS-STC Mixed-Feed System

Redistribution Reactor at Bottom of DCS Column II



SILICON MATERIAL TASK

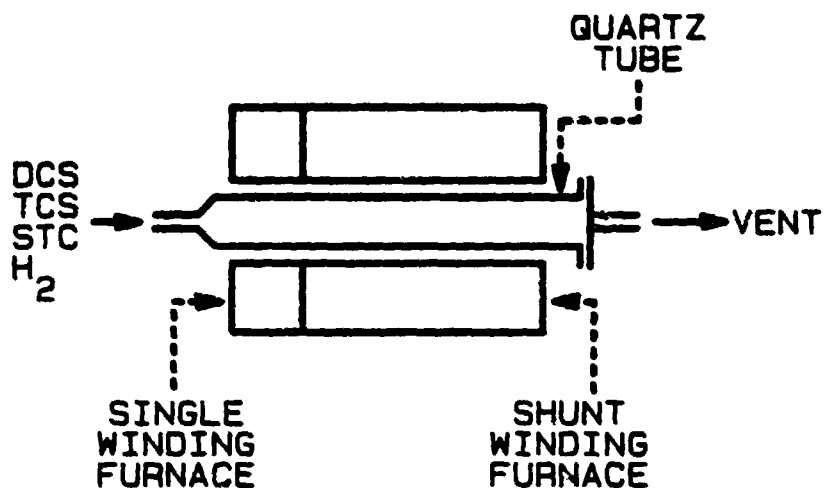
Low-Cost Silicon Process



Decomposition Goals

- DEPOSITION RATE 2.0 G/H/CM
- CONVERSION EFFICIENCY 40%+
- POWER CONSUMPTION <60 KWH/KG
- RUN TIME 100H+

Quartz Tube Deposition Reactor Unit



DCS Process Data: Intermediate Reactor

Run No.	Feed Type	Run Time (hours)	Rod Diameter (mm)	Silicon Fed ($\text{gh}^{-1}\text{cm}^{-1}$)	Silicon Deposition ($\text{gh}^{-1}\text{cm}^{-1}$)	Conversion (Mole %)	Power Consumption (kWh/kg)
324-481	DCS	40.7	48-51	2.9	1.07	36.3	N.A.
324-482	*DCS	75.1	60-65	2.9	0.96	32.5	N.A.
324-483	*DCS	67.5	63-68	2.9	1.12	38.1	N.A.
325-514	*DCS	78.0	84-89	3.9	1.63	41.9	N.A.
325-515	DCS	31.7	44-46	3.7	1.19	32.4	N.A.

* 5 Hour etch after run completed

SILICON MATERIAL TASK

Intermediate Decomposition Reactor Summary

- DICHLOROSILANE REACTOR OPERATION SIMILAR TO TRICHLOROSILANE OPERATION
- NO VAPOR PHASE NUCLEATION IN THE REACTOR
- ROD SURFACE ACCEPTABLE
- PURITY IS SEMICONDUCTOR GRADE QUALITY
- POST HCL ETCH SELECTIVELY REMOVES SILICON FROM THE BELL JAR

QUESTION:

- CAN DECOMPOSITION GOALS BE ATTAINED USING MIXED FEED?
- CAN CONVERSION AND POWER CONSUMPTION GOALS BE ACHIEVED IN A LARGER DECOMPOSITION REACTOR ?

Purity Data

RXR 324 PURITY DATA FOR ELECTRICALLY ACTIVE ELEMENTS
(Boron, Phosphorus, Carbon)

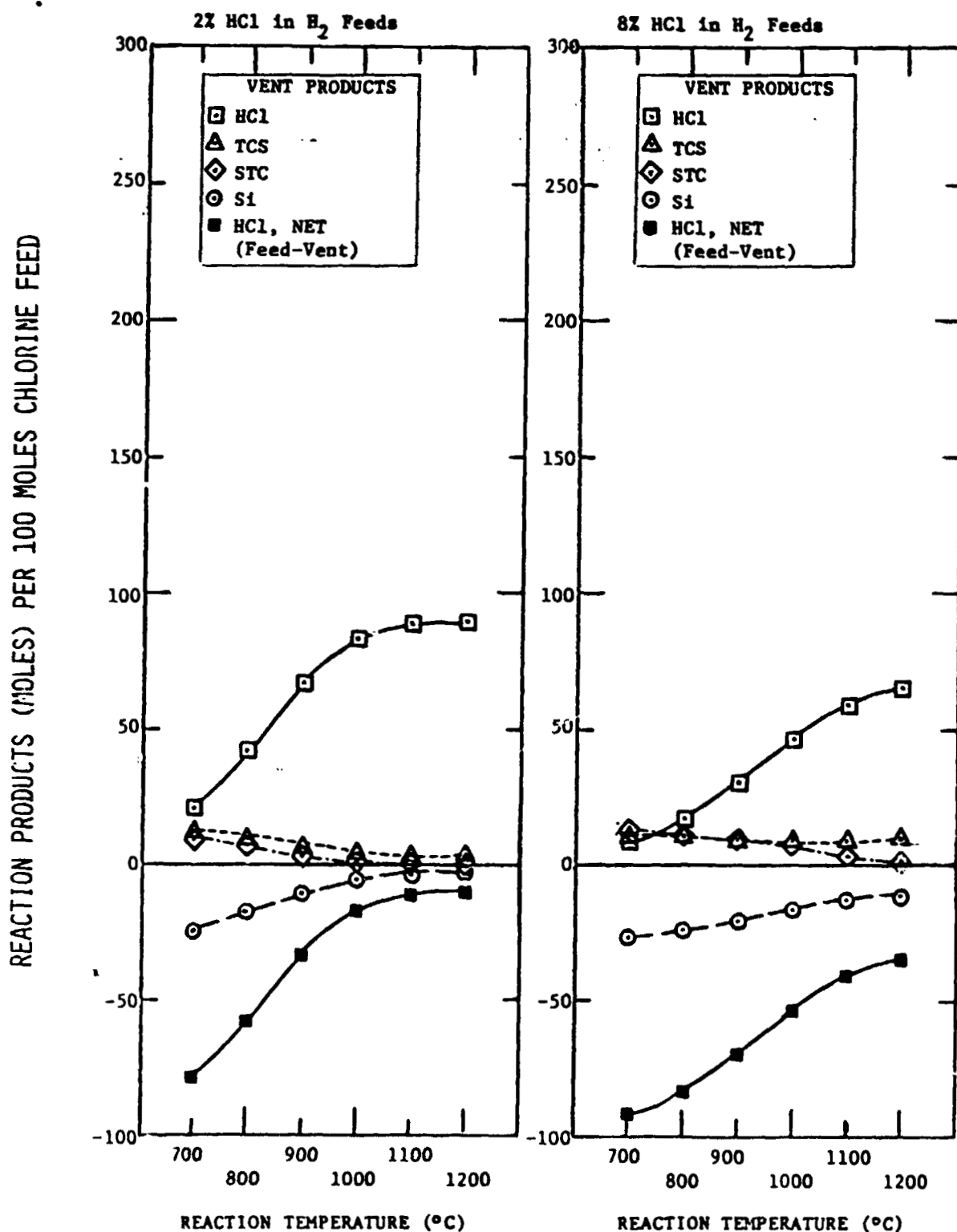
<u>Run No.</u>	<u>Boron (ppba)</u>	<u>Donor (ppba)</u>	<u>Carbon (ppma)</u>
324-419	.08	2.88	0.88
324-420	.08	3.94	0.4
324-421	.08	0.38	
324-422	.06	0.37	
324-423	.06	1.18	
324-424	.06	1.19	
324-425	.06	1.27	
324-426	.06	0.73	0.1
324-427	.06	0.99	
324-428	.05	0.68	0.5
324-429	.07	1.24	
324-430	.07	1.02	
324-431	.07	0.23	0.2
324-432	.07	0.43	0.1
324-433	.07	0.24	
324-434	.04	0.4	0.2
324-435	.04	0.29	0.3
324-436	.30	0.85	
324-437	.10	0.48	
324-438	.10	1.20	0.2
324-439	.08	0.42	0.1
324-440	.04	0.20	0.1
324-441	.04	0.30	
324-442	.06	0.20	0.3
324-443	.06	0.34	0.1
324-444	.04	0.44	0.3
324-445	.06	0.62	
324-446	.06	1.11	
324-447	.06	10.46	
324-450	.05	0.21	
324-451	.05	0.13	0.3
324-452	.05	0.32	0.6
324-453	.06	1.17	
324-454	.06	0.35	0.2
324-455	.06	5.79	0.6
324-456	.07	0.32	0.5
324-457	N.E.	N.E.	
324-458	.06	0.17	0.5
324-459	.06	0.28	0.5
324-460	N.E.	N.E.	
324-461	.10	0.33	0.7
324-462	.10	0.27	0.3
324-463	.10	0.56	
324-464	.10	0.72	
324-465	8.0	7.41	0.5
324-466	.10	0.18	0.3
324-467	.10	0.20	0.6
324-468	.10	0.23	0.5
324-469	N.E.	N.E.	
324-470	1.0	1.21	0.1
324-471	.06	0.69	0.1
324-472	.06	0.24	0.1
324-473	.06	0.73	0.2
324-474	.06	0.25	0.4
324-475	.06	0.39	0.9
324-476	.06	1.83	
324-477	.06	0.87	0.1
# Runs-49	.09 (Avg.)	0.58 (Avg.)	0.3 (Avg.)

SILICON MATERIAL TASK

ORIGINAL PAGE IS
OF POOR QUALITYRXR 325 PURITY DATA FOR ELECTRICALLY ACTIVE ELEMENTS
(Boron, Phosphorus, Carbon)

Run No.	Boron (ppba)	Donor (ppba)	Carbon (ppma)
325-449	.6	30.0	
325-450	.09	0.25	0.7
325-451	.06	1.30	
325-452	.06	0.26	
325-453			
325-454	.07	0.40	0.6
325-455	.10	4.70	
325-456	.51	0.74	
325-457	.19	0.37	0.1
325-458	.19	0.63	0.2
325-459	.08	0.49	
325-460	.06	1.60	0.2
325-461	.08	0.37	0.1
325-462	.06	0.76	
325-463	.06	0.77	
325-464	.06	0.86	
325-465	.06	1.05	
325-466	.06	10.16	
325-467	.06	0.56	0.3
325-468	.05	0.26	0.6
325-469	.06	0.38	0.2
325-470	.06	3.79	0.1
325-471	.04	0.48	0.2
325-472	.06	0.53	0.2
325-473	.06	0.77	0.4
325-476	.04	0.24	0.4
325-477	.04	0.22	0.1
325-478	.04	0.30	
325-479	.03	0.46	0.2
325-480	.08	0.15	0.3
325-481	.10	0.36	0.1
325-482	.10	0.69	0.2
325-483	.10	0.32	0.7
325-484	.06	0.29	0.5
325-485	.06	0.18	0.1
325-486	.10	3.24	
325-487	.10	0.77	0.6
325-488	.10	0.48	0.3
325-489	.10	0.27	0.1
325-490	N.E.	N.E.	
325-491	N.E.	N.E.	
325-492	.06	0.24	0.4
325-493	.10	2.6	0.1
325-494	.10	0.51	0.1
325-495	.10	0.48	0.1
325-496	N.E.	N.E.	
325-497	N.E.	N.E.	
325-498	N.E.	N.E.	
325-499	1.0	0.07	0.1
325-500	.10	0.29	0.3
325-501	.06	0.43	0.1
325-502	.06	0.28	0.8
325-503	.06	0.39	0.1
325-504	.06	0.51	0.1
325-505			
325-506			
325-507	.06	0.34	
325-508	.06	0.20	0.2
† Runs-44	.10 (Avg.)	0.48 (Avg.)	0.3 (Avg.)

Reaction Products vs Reaction Temperature



DCS Purity Summary

REACTOR 324			
# OF RUNS	DONOR PPBA	BORON PPBA	CARBON PPBA
49	0.58	0.09	0.3
3	0.67	0.04	N.A.

REACTOR 325			
44	0.48	0.10	0.3
2	0.38	0.03	N.A.

REACTOR 382			
2	1.41	0.07	N.A.

Intermediate Decomposition Reactor Results

PARAMETER	OBJECTIVE	ACHIEVED
• DEPOSITION RATE (GH ⁻¹ CM ⁻¹)	2.0	1.6 - 2.1
• CONVERSION EFFICIENCY (MOLE %)	>40	43.6
• POWER CONSUMPTION (KWH/KG)	<60	80 - 100
• RUN TIME	100	87
• ROD SURFACE	CZ QUALITY	CZ QUALITY
• PURITY	SEMICONDUCTOR QUALITY	SEMICONDUCTOR QUALITY
• VAPOR PHASE NUCLEATION	N.A.	NONE OBSERVED

SILICON MATERIAL TASK

Problems and Concerns

- ACHIEVING 40 PERCENT CONVERSION EFFICIENCY
- ACHIEVING A POWER CONSUMPTION AT THE REACTOR OF 60 KWH/KG
- QUARTZ BELL JAR INTEGRITY
- ECONOMICS AND FEASIBILITY OF HYDROGENATION PROCESS

SILICON MATERIAL TASK

IN-HOUSE MATERIAL RESEARCH PROGRAM
Si Deposition in FBR System

JET PROPULSION LABORATORY

G.C. Hsu

2-in. FBR Program

VARIABLES

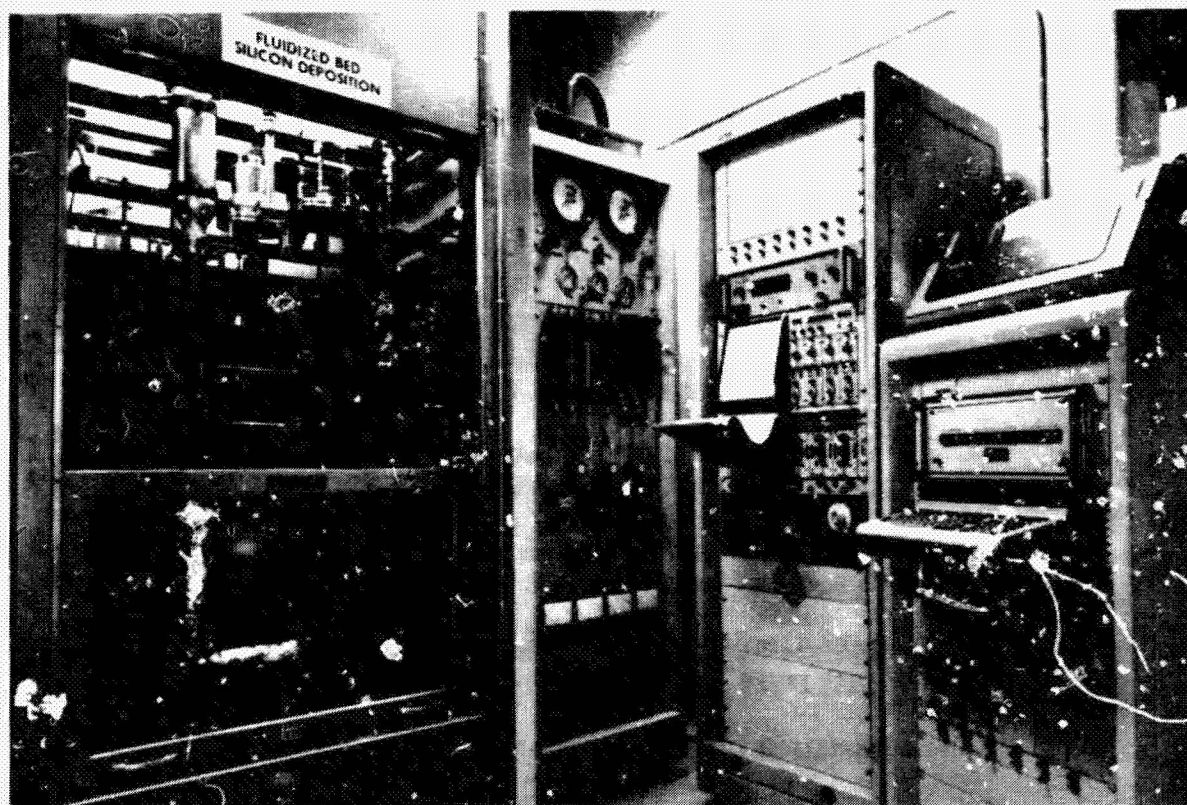
- TEMPERATURE - 650°C, 700°C, 750°C
- SILANE CONC. - 20%, 50%, 65%
(SiH_4 , H_2)
- U/U_{mf} - 1 TO 6

FIXED PARAMETERS:

- SEED PARTICLE SIZE - 335 μm (AVERAGE)
(POLY SI - SEMICONDUCTOR GRADE)
- INITIAL BED WEIGHT ~400 gm
~6 inch HEIGHT
- DISTRIBUTOR: 200 MESH SCREEN ON S.S. SUPPORT WITH
1/16" HOLES
- DURATION OF RUN: UP TO 1 hour (16 RUNS)

SILICON MATERIAL TASK

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



FBR Si Deposition

SILICON MATERIAL TASK

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

SEED

POLY SI PARTICLE ($\sim 335 \mu\text{m}$)

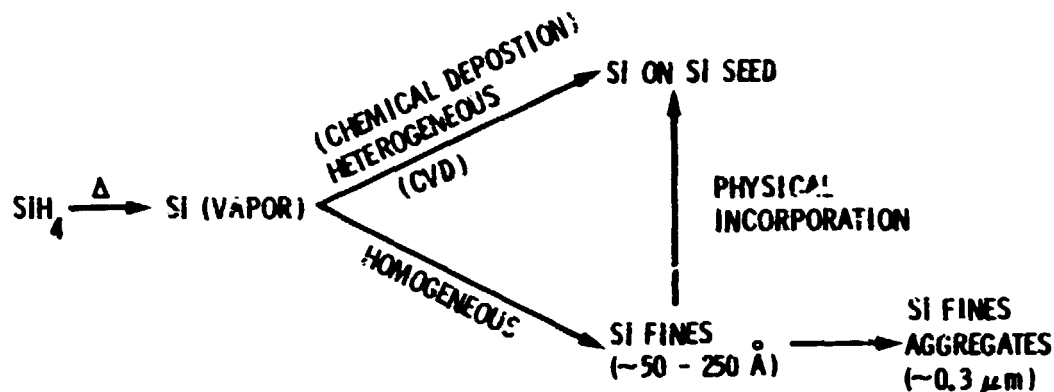


PRODUCT

CONDITIONS: 2" FBR
650°C, 50% SiH_4/H_2 , $U/U_{mf} = 6$
DEPOSITION RATE: $> 1 \mu\text{m}/\text{min}$
DENSE FREE-FLOWING PARTICLES



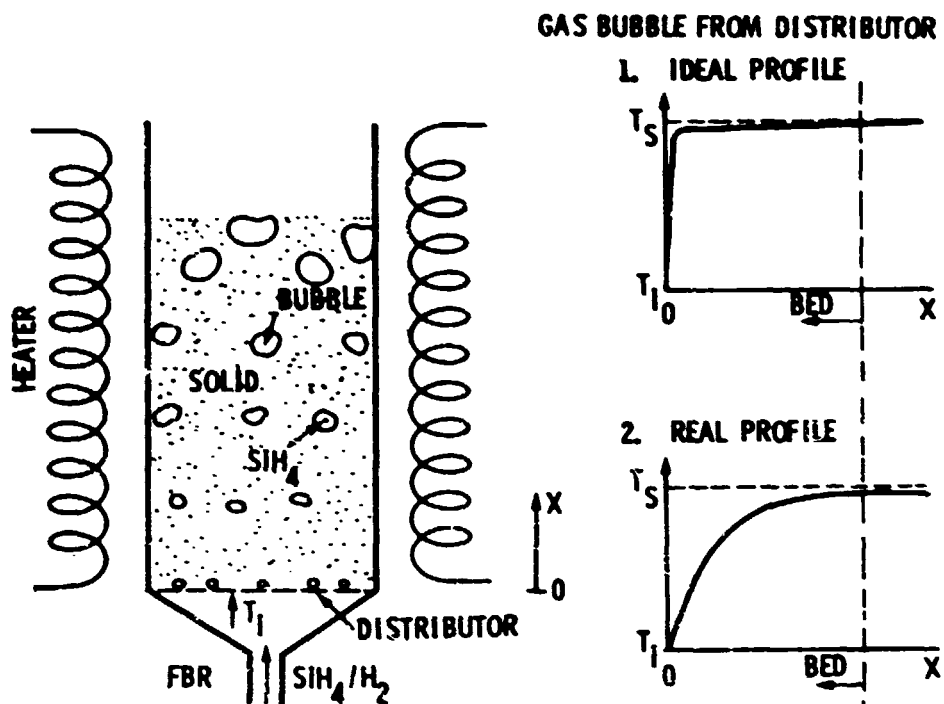
Growth Mechanism



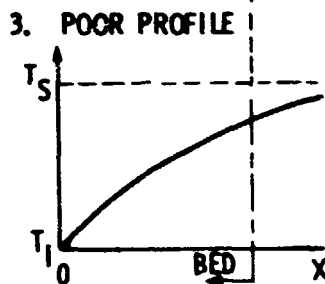
Color of Si Fines

- SI FINES - SUBMICRON POWDERS SAME AS CFP SI FINES
- COLOR CHANGES AT DIFFERENT TEMPERATURES
 - SIZE AT DIFFERENT TEMPERATURES
 - HYDROGEN CONTENT SiH_x
(E.G., $\text{SiH}_{0.2}$ STABLE AT ROOM TEMPERATURE AND DOES NOT DECOMPOSE IN AIR)
E.G.,
 - AT 650°C - DULL BLACK (FINELY-DISPERSED SI)
 - AT 750°C - DARK BROWN
- COLOR IS REFLECTED IN FBR PRODUCT PARTICLES (FBR COATING IS COHERENT AND WITH SMALL POROSITY)

Heat and Mass Transfer in Fluidized Bed

**LOW GAS BUBBLE TEMPERATURE**

- LARGE GAS BUBBLES FROM DISTRIBUTOR (CONVECTIVE HEAT TRANSFER)
- INSUFFICIENT HEATING FOR THE BOTTOM HEATER ZONE
- HIGH GAS VELOCITY
- INSUFFICIENT BED HEIGHT
- LOW SOLID TEMPERATURE
- POOR GAS PREHEATING



SILICON MATERIAL TASK

Dust Formation

- LESS THAN 10% DUST, FOR PROPER FLUIDIZED BED OPERATION
- TO MAINTAIN THE SAME U/U_{mf} FOR SIMILAR FLUIDIZATION QUALITY,
 $U_{650^{\circ}\text{C}} > U_{750^{\circ}\text{C}}$
AT 650°C , REACTION ABOVE THE BED LED TO HIGHER DUST FORMATION (e.g. UP TO 17%)
- DUST LEVEL INCREASES MODERATELY WITH SILANE CONCENTRATION
- DUST COLLECTION INCREASES MODERATELY WITH U/U_{mf}

Bed Agglomeration

- NO BED AGGLOMERATION FOR PROPER FLUIDIZATION
 - DISTRIBUTOR: FLOW PATTERN AND GAS BUBBLE SIZE
 - VIGOROUS AGITATION: $U/U_{mf} \geq 3$
 - FAST HEATING AT THE REACTOR BOTTOM (REACTION) REGION

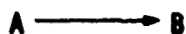
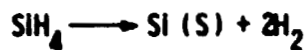
Key FBR Design Parameters

- DISTRIBUTOR
- HEATER

Key Operating Parameters

- TEMPERATURE ($650^{\circ}\text{C} \leq T \leq 750^{\circ}\text{C}$)
- FLUIDIZATION QUALITY (e.g. $3 \leq U/U_{mf} \leq 6$)
- BED HEIGHT ($L/D \geq 3$ FOR 2" FBR)

Kinetic Model
Overall Growth, Chemical and Physical



$$\frac{dC_B}{dt} = k S C_{A0}$$

ASSUME N (No. OF SEED PARTICLES/UNIT BED VOLUME) IS CONSTANT

$$S = 4\pi r^2 N$$

$$C_B = \frac{4}{3} \pi r^3 N \rho / M_B$$

$$W_B = \frac{4}{3} \pi r^3 N \rho$$

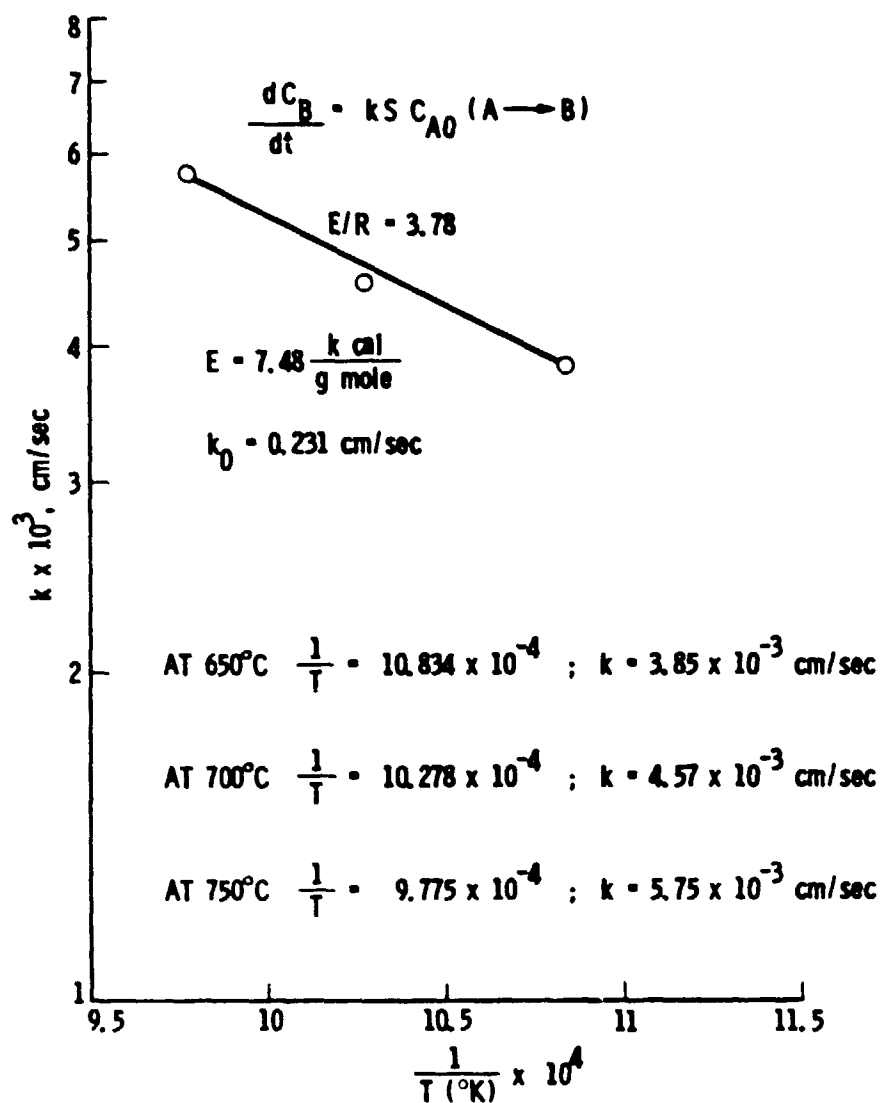
$$S = \left[4\pi N \left(3 M_B / \rho \right)^2 \right]^{1/3} C_B^{2/3} = d C_B^{2/3}$$

$$\therefore \frac{1}{d C_{A0}} \int_{C_{B0}}^{C_B} \frac{dC_B}{C_B^{2/3}} = kt \quad , \quad k = 3 \left(C_B^{1/3} - C_{B0}^{1/3} \right) / d C_{A0} t$$

EQUIVALENT GROWTH MODEL (SEM)

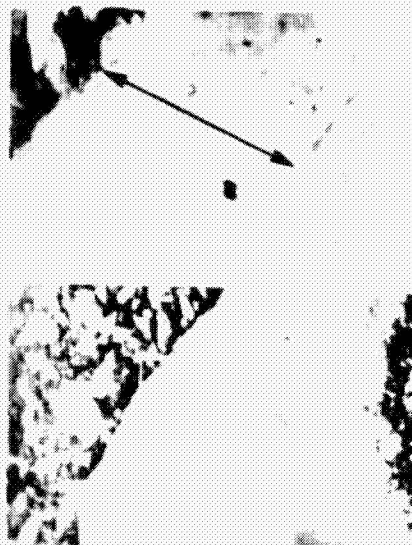
$$\frac{dr}{dt} = k C_{A0} M_B / \rho \quad , \quad k = (r - r_0) \rho / C_{AG} M_B t$$

First-Order Heterogeneous Deposition Model



FBR Si Particle Growth by SEM
(2-in. FBR, 650°C, 50% SiH₄/H₂, U/U_{mf} = 6)

t = 30 min
x = 200/1000



t = 45 min
x = 200



t = 60 min
x = 200



SILICON MATERIAL TASK

Particle Growth

I VIA KINETIC MODEL:

- MODEL ASSUMES
- UNIFORM DEPOSITION ACROSS THE BED
 - NO COATING POROSITY
 - CONSTANT VOLUME IN BED

ILLUSTRATION: (TYPICAL VALUES IN THE OPERATING RANGE)

$$S = 94 \text{ cm}^2/\text{cm}^3, C_{A0} = 0.01 \text{ gmole/l}$$

$$\frac{dC_B}{dt} = 0.5 C_{A0} = 0.005, \frac{dr}{dt} = 0.3 \text{ } \mu\text{m/min}$$

- DEPOSITION RADIUS FROM KINETIC MODEL IS THE LOWER LIMIT FOR ACTUAL GROWTH

II VIA SEM MEASUREMENTS

$$\left. \begin{array}{l} \text{AT } 650^\circ\text{C } \Delta r_{60 \text{ min}} = 62 \text{ } \mu\text{m} \\ \text{AT } 700^\circ\text{C } \Delta r_{50 \text{ min}} = 70 \text{ } \mu\text{m} \\ \text{AT } 750^\circ\text{C } \Delta r_{60 \text{ min}} = 100 \text{ } \mu\text{m} \end{array} \right\} \left(\frac{\Delta r}{\Delta t} \right)_{750^\circ\text{C}} = 1.67 \text{ } \mu\text{m/min}$$

- DEPOSITION RADIUS FROM SEM MEASUREMENTS IS THE UPPER LIMIT FOR ACTUAL GROWTH

Mass Balance Deposition Rate

(2" FBR, T = 700°C, CONC. = 50% SILANE, U/U_{mf} = 6)

$$\begin{aligned} \text{DEPOSITION RATE} &\cong 8.24 \text{ gm/min} \\ &\cong 0.5 \text{ kg/hr} \end{aligned}$$

PROJECTION:

FOR 6" FBR AT 50% SILANE, RATE ~ 4.5 kg/hr

FOR 6" FBR AT 100% SILANE, RATE ~ 9 kg/hr

(ASSUME 70% ON STREAM TIME, DEPOSITION RATE ~ 55 MT/yr)

~ TWO 6" FBR's FOR 100 MT/yr

COMPARISON:

SIEMENS TYPE OF REACTOR (HSiCl₃)

0.3 - 0.5 kg/hr (LENGTH 40 in., dia 3 in., 6 rods)

DEPENDING ON ROD DEPOSITION QUALITY

(e.g. 20 in. DIAMETER x 4 ft BELL JAR REACTOR)

Status of FBR Program

- IN 2 Inch FBR SYSTEM:
 - ESTABLISHED CHEMISTRY AND PRODUCT MORPHOLOGY
 - IDENTIFIED OPERATING WINDOW AND DESIGN PARAMETERS
 - DETERMINED DEPOSITION KINETICS
- IN 6 Inch FBR SYSTEM:
 - STUDY DISTRIBUTOR FOR PRACTICAL FLOW (MINIMIZING WALL EFFECT)
 - STUDY BED DEPTH FOR INCREASING FINE COLLECTION EFFICIENCY
 - STUDY THE LIMIT OF SILANE CONCENTRATION
 - STUDY SEED PARTICLE SIZE EFFECT
 - STUDY PRODUCT PURITY

SILICON MATERIAL TASK

ORIGINAL PAGE IS
OF POOR QUALITYBasic JPL 6-in. FBR Experimental Plan
Current Phase (From May 1982)COMMON CONDITIONS: 700°C, U/U_{mf} = 5, PARTICLE SIZE RANGE: 150-250 μ (MESH No. 60-100)

BASIC RUN No.	PURPOSE	TYPE (OR REMARK)	SILANE CONC.	BED DEPTH	DURATION
1	ESTABLISH BASELINE CONDITION	POROUS CARBON DISTRIBUTOR	20%	6 in.	1 hr.
2	BED DEPTH TEST	POROUS CARBON DISTRIBUTOR	20%	12 in.	1 hr.
3	DISTRIBUTOR TESTS	SINTERED METAL (1" THICK)	20%	6 in.	1 hr.
4	DISTRIBUTOR TESTS	CHOSEN FROM COLD FLOW TEST, METAL PLATE POROUS SCREEN	20%	6 in.	1 hr.
5	DISTRIBUTOR TESTS	NOZZLE-CONE DISTRIBUTOR	20%	6 in.	1 hr.
6	REPRODUCIBILITY AND LONG DURATION RUN	DISTRIBUTOR SELECTED FROM DISTRIBUTOR TESTS (FROM RUN No. 6 ON)	20%	6 in.	3 hr. (SAMPLES: 0, 30 min., 1 hr., 2 hr., 3 hr. *)
7	CONCENTRATION LIMIT TEST	DISTRIBUTOR SELECTED FROM DISTRIBUTOR TESTS (FROM RUN No. 6 ON)	0-100% (10% INCRE)	6 in.	TIME AS REQUIRED
8	DEPOSITION KINETICS	CONTROL RUN FOR PURITY ANALYSIS (ALSO WITH PARTICLE DISTRIBUTION ANALYSIS *)	50%	6 in.	1 hr. (0, 15, 30, 45, 60 min. *)
9	PARTICLE DEPOSITION DISTRIBUTION	SIMULATED SEED SIZE ADDED (* * 10% SEED 44-74 μ , MESH No. 325-200)	50%	6 in.	1 hr. (0, 15, 30, 45, 60 min. *)
10	HIGH CONCENTRATION TEST	(COULD USE 12" BED DEPTH, IF NEEDED)	100%	6 in.	30 min.
11	PURITY EVALUATION	USE QUARTZ LINER (NEUTRON ACTIVATION)	50%	6 in.	1 hr.

Large-Area Silicon Sheet Task

A.D. Morrison, Chairman

Presentations were made by seven contractors and by JPL on silicon (Si) sheet efforts and related work.

Westinghouse Electric Corp. reviewed progress on the Si dendritic-web growth contract. A set of new computer models was used successfully to define a growth system configuration that was then built and used to grow web with lower thermally generated stress than has any configuration previously developed by empirical means.

Mobil Tyco Solar Energy Corp., which is conducting research on the edge-defined film-fed growth (EFG) method of making Si ribbon, reported that a significant increase in cell efficiency was demonstrated in large areas (50 cm^2) of ribbon grown at high speed (3.5 cm/min). The best cells gave 11.7% efficiency (AM1 and AR coated), just short of this year's goal of 12%.

In the Semix Inc. semicrystalline cast Si program, a technique was developed to determine base resistivity and carrier lifetime in semicrystalline wafers. Also, 100-cm^2 cells of 13.5% efficiency (AM1) were made in limited quantities.

Kayex Corp., which has just completed its effort on advanced Czochralski Si ingot growth, reviewed achievements since contract inception. These included automated growth of 150 kg of 15-cm-dia ingot material per crucible, with after-growth yields of greater than 90% at throughputs of 1.5 kg/h.

Cornell University reported on scanning transmission electron microscopy (STEM) and microprobe investigations of processed EFG ribbon. The following process-induced changes in the defect structure (as compared to unprocessed EFG ribbon) were noted:

- (1) Processing introduces regularly spaced, sub-boundary-like dislocation arrays in the bulk (base section) of the material.
- (2) Some (but not all) of the dislocation nodes in these networks act as nucleation centers for small ($d < 100 \text{ Angstrom}$) precipitates.
- (3) Large precipitates ($d \approx 1 \mu\text{m}$) are formed in the bulk of the material.

The chemical composition of the large precipitates was studied by non-dispersive X-ray analysis in a JEOL 200 CX STEM and by dispersive analysis (for C) in a JEOL 733 Superprobe. Elements identified were Ti, Fe, W, Mo, Cl, Ca and C. None of these elements were found in the matrix. It appears that the precipitates act as gettering centers for impurities. Cl is traceable to the Cl bakeout of the graphite dies.

The structural arrangement and the electrical activity of dislocations at or close to the central twin plane in processed material was studied by electron-beam induced current (EBIC) microscopy on a shallow-bevel specimen.

LARGE-AREA SILICON SHEET TASK

The majority of the dislocations in the twin plane are regularly spaced and mostly straight arrays of dislocation of like sign, accommodating a tilt component. Dislocation density in the twin plane is high, and the dislocations are effective recombination centers. Inspection of straight sections under higher magnification shows that the electrical activity varies along the dislocation, possibly due to precipitates (TEM will be carried out after completion of EBIC to clarify this point). Temperature-dependent EBIC is being carried out in order to determine the electronic energy levels associated with the various sections.

JPL in-house research program results were presented on the electrical and structural properties of grain boundaries in silicon, particularly those concerning electrical and enhanced diffusion along the grain boundaries.

Temperature-dependence measurements of zero-bias conductance, a photo-conductivity technique, and deep-level transient spectroscopy (DLTS) were developed to investigate potential barrier, carrier recombination velocity, and electronic states, respectively. The studies of potential barrier have revealed that considerable variation in the activation energy along grain boundaries often exists, presumably due to variation of local disorders; the activation energy usually increases with annealing temperature, and the potential barrier decreases with increasing light intensity. The recombination velocity measurements show that the velocity increases with boundary state density and light intensity. The preliminary result from the DLTS experiments indicates a trend: the density of states generally increases with the distance from the edges of the band gap. However, the details vary considerably from sample to sample, a result that can be attributed to local variation of disorders.

A grooving and staining technique, secondary ion mass spectroscopy, and EBIC measurements in scanning electron microscopy were used to study enhanced diffusion of phosphorus at grain boundaries in polycrystalline silicon. The results show that the enhanced diffusion occurs only at high-order grain boundaries having high carrier recombination and the depth of the enhanced diffusion varies drastically from boundary to boundary, making any quantitative measurement difficult unless the boundary can be characterized well.

The University of Illinois at Chicago is studying the fundamental mechanisms of abrasion and wear and the deformation of Si by a diamond in various fluid environments. The abrasion rates and depths of damage of $\langle 100 \rangle$ and $\langle 111 \rangle$ p-type Si in three fluid environments (acetone, ethanol, and water) were determined, and the surface deformation mechanism was found to change when the fluid was varied.

Applied Solar Energy Corp. presented results on the efficiency of solar cells made from EFG ribbon and Semix Inc. material. For EFG material, a baseline process was applied to ribbons grown with or without CO_2 in the ambient. In general, cells made from EFG ribbon grown in CO_2 performed better. However, the results from both groups were lower than those reported previously.

For the Semix material, work continued on Ingot 5848-13C. High-efficiency processes were applied and the results were presented. A series of more severe gettering schedules was performed on identified portions of the

LARGE-AREA SILICON SHEET TASK

ingot. It was shown that short-circuit current improved with gettering up to a limiting value (which was still below that of the control cell). Light-biased diffusion length measurements showed that there was a negative light-biased effect (the minority carrier diffusion length decreased) that limited the improvement of short-circuit current in the more severely gettered cells. Also, the baseline process was applied to 10 x 10-cm Semix wafers randomly selected (not from a single ingot).

ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

<u>Technology</u> Single crystal ribbon growth	<u>Report Date</u> 04/21/82
<u>Approach</u> Silicon dendritic web growth <u>Contractor</u> Westinghouse Electric Corp. Research & Development Center JPL Contract 955843	<u>Status</u> <ul style="list-style-type: none"> • First generation computer models developed and verified • Experimental web growth machine completed and operational • Melt-replenished steady-state web growth demonstrated at intermediate growth rate of $7 \text{ cm}^2/\text{min}$ • Web growth rate of $27 \text{ cm}^2/\text{minute}$ demonstrated under transient conditions • Growth width To 5 cm demonstrated
<u>Goals</u> <ul style="list-style-type: none"> • Develop computer models for characterizing and understanding web growth • Develop experimental web growth machine for use with models • Demonstrate melt-replenished steady-state web growth • Demonstrate $25 \text{ cm}^2/\text{minute}$ web growth rate • Demonstrate 5 cm web growth width 	

Program Emphasis

- Deformation Is Major Limitation Of Ribbon Width And Throughput Rate
- Deformation Is Correlated To Thermally Generated Stress
- Computer Models Provide Understanding Of Web Growth And Thermal Requirements For Stress Reduction And Optimized Throughput

LARGE-AREA SILICON SHEET TASK

Principal Activity

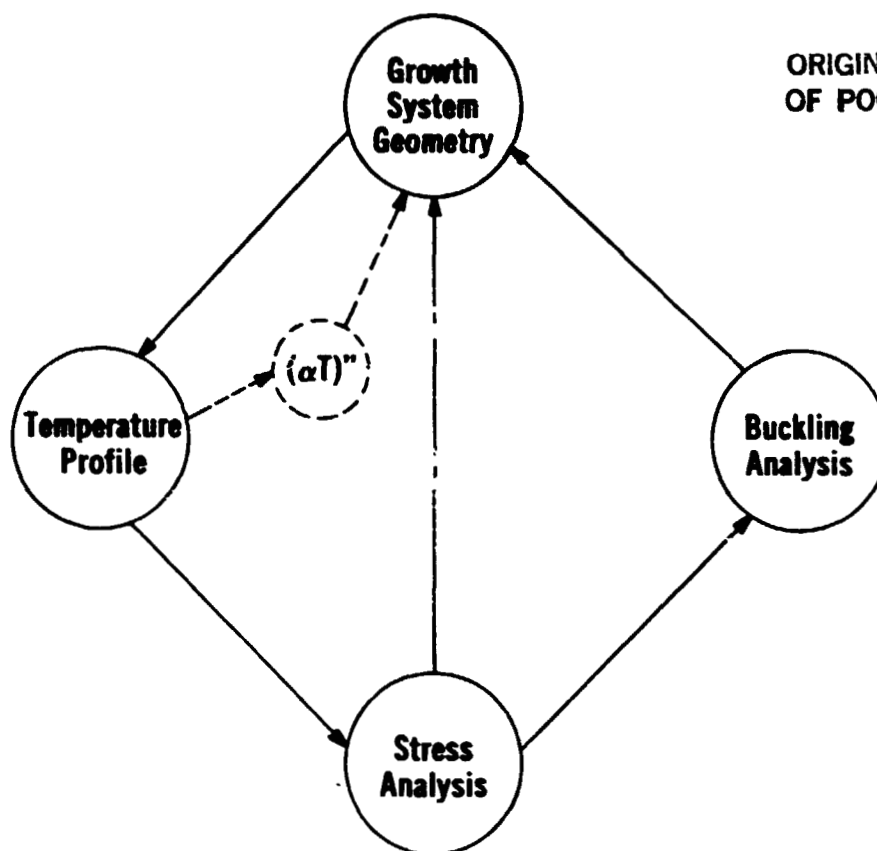
- **Develop Computer Models For Web Growth**
- **Develop Experimental Web Growth Machine Capable Of Automated, Melt-Replenished, Steady-State Growth**
- **Utilize Computer Models And Experimental Growth Machine For Development Of Advanced Web Growth**

Computer Models to Characterize Web Growth

- **Compute Web Temperature Distribution Generated By A Specified Growth Configuration**
- **Compute Thermal Stress Generated By A Specified Web Temperature Distribution**
- **Compute The Critical Buckling Conditions For A Specified Thermal Stress**

LARGE-AREA SILICON SHEET TASK

Application of Computer Models

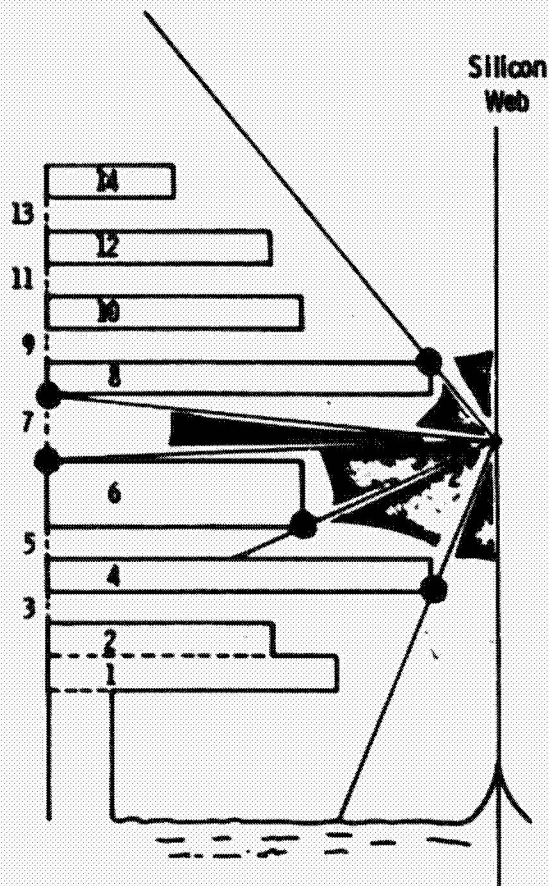


Status of Computer Models

- Web Temperature Model Has Been Expanded To Be More Definitive And Has Been Verified As Adequate For Next Generation Of Increased Web Throughput
- Thermal Stress Model Is Complete And Verified
- Critical Buckling Model Is Complete And Verified

LARGE-AREA SILICON SHEET TASK

Viewing Regions From a Point on the Web



Steady-State Web Growth Is Necessary

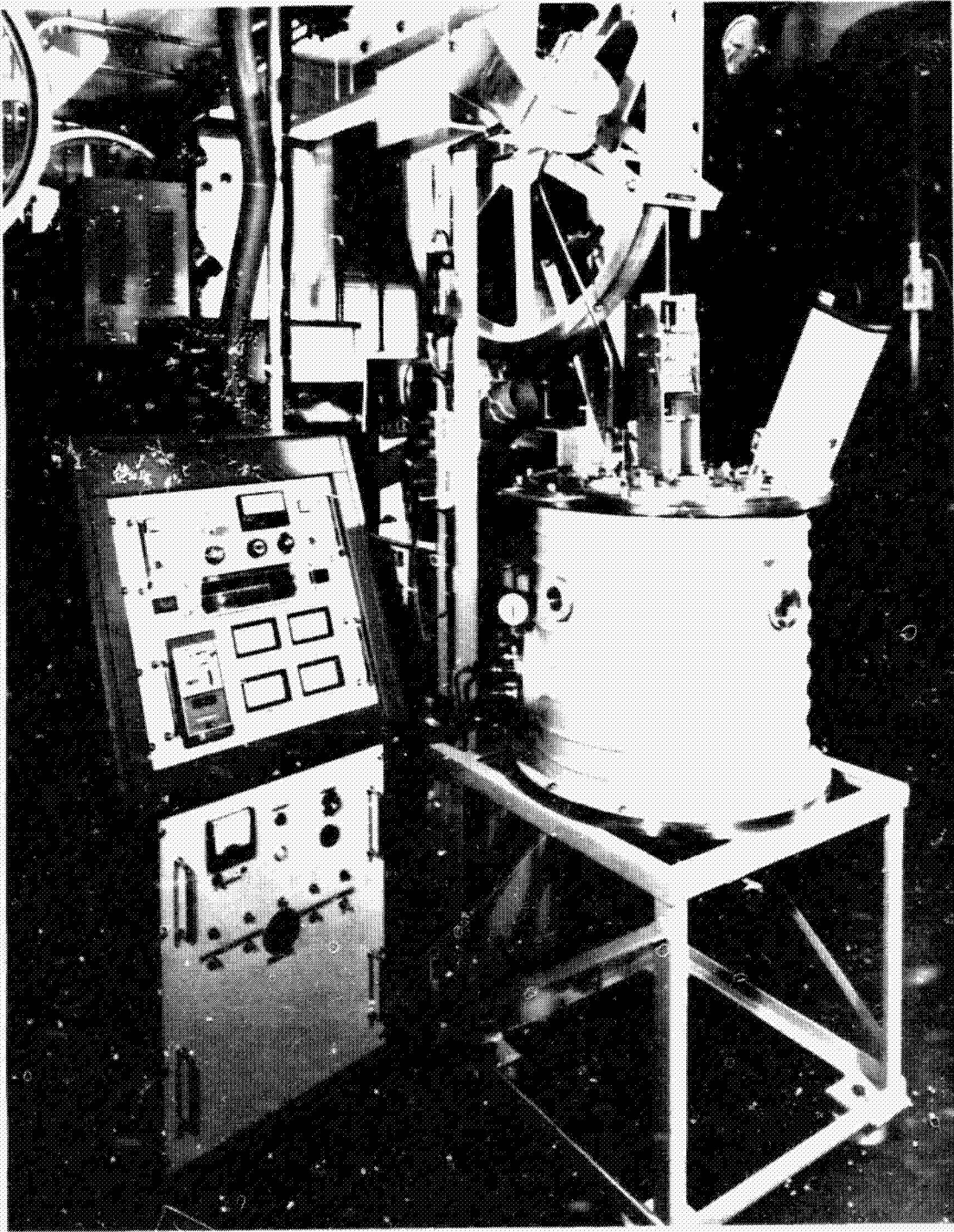
- For Process Analysis, Understanding And Improvement
- For Subsequent Process Standardization

LARGE-AREA SILICON SHEET TASK

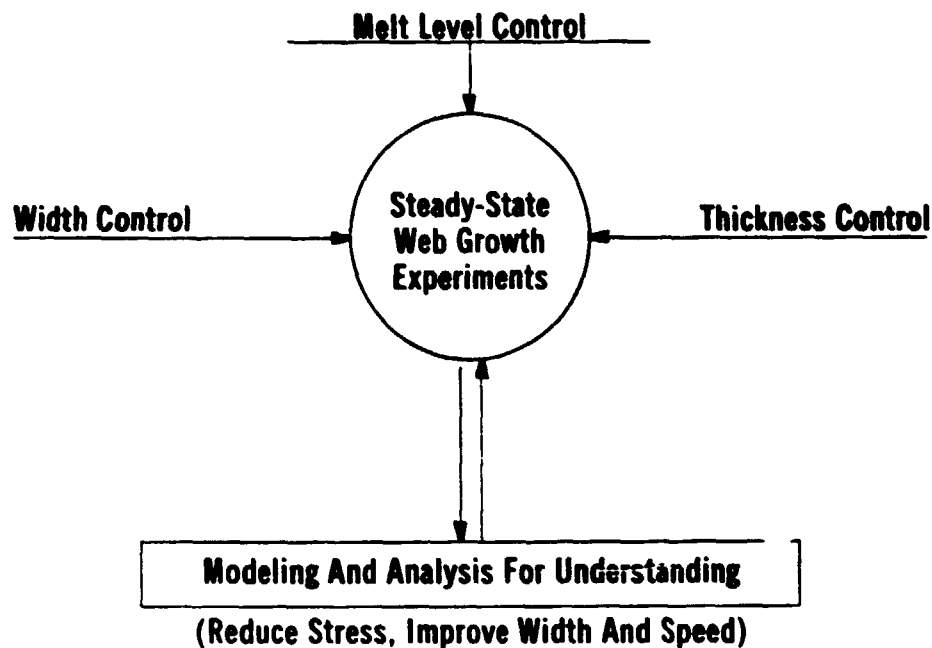
Experimental Web Growth Machine Provides Basic Requirements for Automated Steady-State Growth:

- **Flat Temperature Profile In Growth Region Of Melt**
- **Controlled Constant Temperature**
- **Controlled Constant Melt Level**
- **Controlled Constant Thickness**
- **Controlled Constant Width**

Dendritic Web Experimental Sheet Growth Unit (ESGU)



Combined Use of Models and Experimental Web Growth



Results of First Use of Models

- In First Application Models Were Verified By Comparison With A Previously Characterized Growth Configuration. The Model Identified System Limitations And Suggested Modifications Which Resulted In Width Increase Of 25% (To 5 cm)
- Automated Steady-State Web Growth Achieved At Intermediate Rate ($7 \text{ cm}^2/\text{minute}$)
- Use Of Models Proven As Route For Understanding And Improvement Of Web Growth

LARGE-AREA SILICON SHEET TASK

Problems and Concerns

- **Present - None. Understanding And Improvement Of Process Proceeding As Planned**
- **Future - Availability Of Low-Cost Polysilicon In Pellet Form**

Summary

- **Computer Models Of Web Growth Completed And Verified**
- **Experimental Web Growth Machine Proven In Automated Steady-State Growth**
- **Web Growth Improved By Application Of Models**

EDGE-DEFINED FILM-FED GROWTH

MOBIL TYCO SOLAR ENERGY CORP.

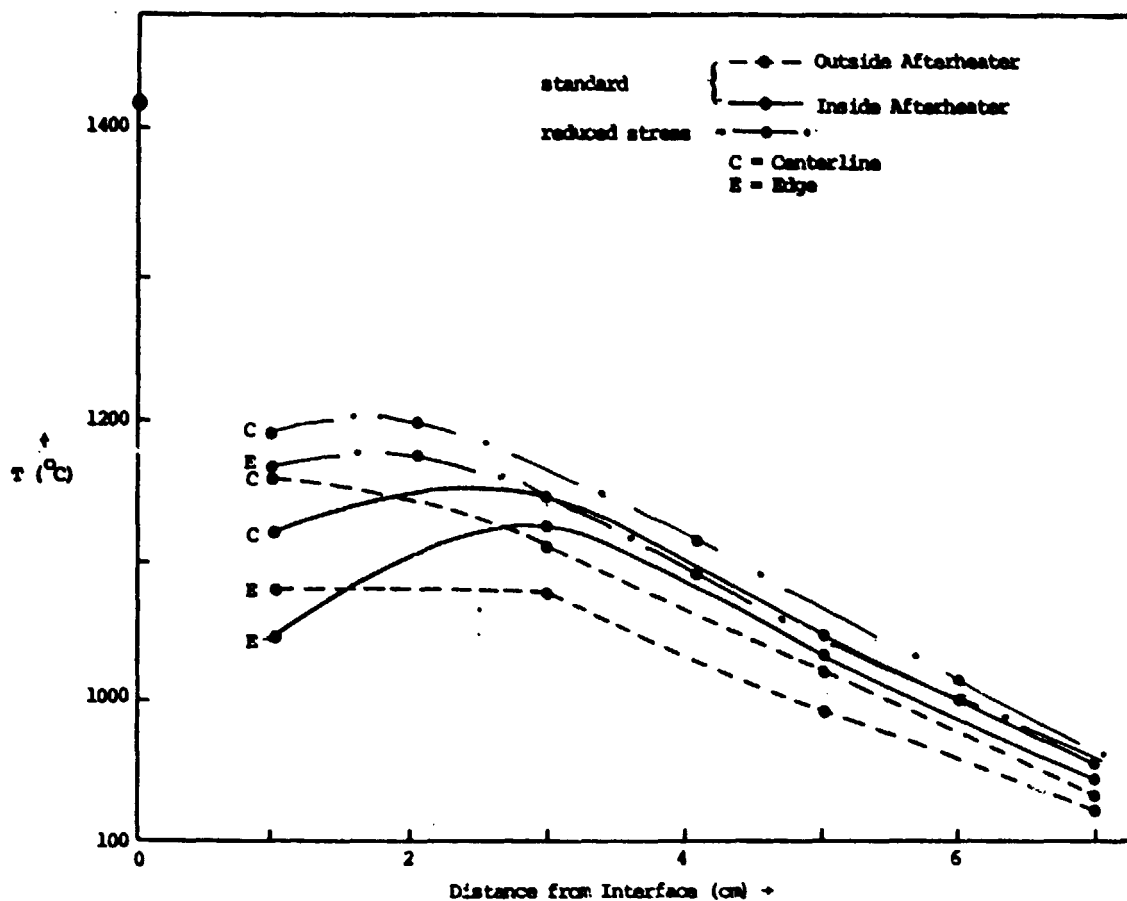
TECHNOLOGY LARGE AREA SILICON SHEET BY EFG	REPORT DATE 4/21/82
APPROACH MULTIPLE GROWTH OF 10 CM WIDE SILICON RIBBON AT 4 CM/MINUTE. CONTRACTOR MOBIL TYCO SOLAR ENERGY CORPORATION	STATUS <ul style="list-style-type: none"> ● CARTRIDGE DESIGN CHANGES HAVE REDUCED RIBBON STRESS AND BUCKLING LEVELS FOR 200 μM THICK RIBBON TO LEVEL WHERE FABRICATION OF LARGE AREA CELLS IS POSSIBLE. ● LARGE AREA (50 cm^2) CELLS OF 11.7% (AM1 AND AR COATED) HAVE BEEN ACHIEVED FOR RIBBON GROWN IN HIGH SPEED SYSTEM (AT 3.5 CM/MINUTE). ● NEW MULTIPLE RIBBON FURNACE HAS BEEN BUILT AND TESTED (OPERATION HAS BEEN SET ASIDE DUE TO REDUCTION OF PROGRAM).
GOALS <ul style="list-style-type: none"> ● REDUCE STRESS AND IMPROVE FLATNESS OF RIBBON GROWN AT 4 CM/MINUTE AND 200 μM THICKNESS. ● DEMONSTRATE 12% CELL EFFICIENCY ON LARGE AREAS (50 cm^2) FOR RIBBON GROWN IN HIGH SPEED SYSTEM. ● DESIGN, CONSTRUCT AND OPERATE NEW MULTIPLE RIBBON FURNACE FOR GROWTH OF FOUR 10 CM WIDE RIBBONS. 	

Progress in Stress Studies

- INFLUENCE OF CARTRIDGE COMPONENT DESIGN ON STRESS AND BUCKLING LEVELS IN 10 CM WIDE RIBBON HAS BEEN IDENTIFIED:
 - TEMPERATURE FIELDS IN LINEAR COOLING PLATES OF SEVERAL DIFFERENT DESIGNS HAVE BEEN MEASURED.
 - IMPROVED FLATNESS WAS ACHIEVED IN 200 μ M THICK RIBBON GROWN WITH A MODIFIED DESIGN CARTRIDGE.
 - CHANGE IN HORIZONTAL ISOTHERM SHAPE IS PROBABLE CAUSE FOR REDUCED STRESS AND BUCKLING LEVELS.

LARGE-AREA SILICON SHEET TASK

ORIGINAL PAGE IS
OF POOR QUALITY



Comparison of center and edge temperature profiles in 10 cm cartridge linear cooling plates.

Stress Studies: Plans

- CAPABILITY IS NEEDED TO PREDICT: (i) MOVING RIBBON TEMPERATURE PROFILES GIVEN SYSTEM COMPONENT TEMPERATURES AND GEOMETRY, AND (ii) STRESS DISTRIBUTIONS AND BUCKLING THRESHOLDS FROM RIBBON TEMPERATURE FIELDS.
- EMPIRICAL APPROACH WILL: (i) GUIDE THEORETICAL STUDIES AND ESTABLISH BOUNDARY CONDITIONS FOR MODELING, AND (ii) ARRIVE AT REDUCED STRESS GROWTH CONFIGURATIONS THAT ARE COMPATIBLE WITH ACCEPTABLE GROWTH CONDITIONS AT 4 CM/MIN.

IMPORTANT TO SYNTHESIZE OUT OF THIS APPROACH A SYSTEM THAT WILL PRODUCE 200 μ m THICK RIBBON AT 4 CM/MIN WITH SUFFICIENTLY LOW STRESS AND FLATNESS TO MEET DEMANDS IN YIELD AREA.

Progress in Quality Improvement

- SIGNIFICANT IMPROVEMENT IN CELL EFFICIENCY OF HIGH SPEED GROWN RIBBON TO 11-12% HAS BEEN ACHIEVED.
 - AMBIENT CONTROL HAS PROVEN TO BE VERY IMPORTANT PARAMETER IN OBTAINING CONSISTENT ELECTRONIC QUALITY RIBBON.
 - RIBBON EXIT GAS SEAL, MORE UNIFORM INTERFACE GAS CONTROL SYSTEMS IMPLEMENTED SUCCESSFULLY.

LARGE-AREA SILICON SHEET TASK

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OF POOR QUALITY

SPV Diffusion Length Data for 10 cm Wide Ribbon Grown with
Stretched Cartridge in Machine 17. Bulk Melt Doping was
4 Ω -cm for All Runs.

Run No. and Segment	M.Z. Argon Flow Rate (ℓ /minute)	Cartridge Gas Composition	Cartridge Gas Flow Rate (ℓ /minute)	Gas Seal	Speed (cm/minute)	L_D (μ m)
17-199-1A	10	argon	1.5	no	3.0 - 3.2	23.0
-1C					3.8	35.0
17-200-1A	6	argon	1.0	no	3.5	33.0
-1D		0.45% CO_2 + 45 ppm O_2	1.8		3.8 - 3.9	43.0
17-201-1B	6	argon	1.0	yes	3.3	33.6
-1D	3				3.3 - 3.4	30.0
17-202-1A	3			yes	3.5 - 3.6	43.0
-1B	2				3.8	39.0
-1C	2				3.8	52.0
-1D	0				3.8	36.0
17-203-1A	6	argon	1.0	yes	3.3	41.0
-1C		0.17% CO_2 + 18 ppm O_2	1.2		3.5	45.0
17-204-1A	6	argon	1.0	yes	3.5	49.0
-1C		0.29% CO_2 + 29 ppm O_2	1.4		3.5	36.0
17-205-1B	6	0.17% CO_2 + 17 ppm O_2	1.2	yes	3.5	45.4

Solar Cell Data for Phosphine Processed Large Area (50 cm^2)
Solar Cells Made from 10 cm Wide Ribbons.

100 mW/cm^2 , Xenon Light, 28°C , AR Coated.

Run No.	Growth Ambient	Speed (cm/min)	Average Resistivity ($\Omega\text{-cm}$)	Diffusion Length (μm)	Cell Parameters				
					J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)	Mean η (%)
17-143	0.2% CO_2	2.5	1.5	27	26.5	0.523	0.608	8.4	9.6
					26.5	0.531	0.705	9.9	
					27.7	0.534	0.677	10.0	
					26.2	0.530	0.699	9.7	
					28.6	0.538	0.634	9.7	
17-174	Quartz in melt	3.5	1.0	35	26.2	0.529	0.717	9.9	9.4
					26.6	0.533	0.896	9.9	
					25.3	0.527	0.667	8.9	
					26.7	0.534	0.697	9.9	
					26.8	0.539	0.735	10.6	
17-175	0.2% CO_2 + 30 ppm O_2	3.5	1.0	36	27.7	0.545	0.706	10.7	10.3
					26.1	0.537	0.720	10.1	
					27.5	0.547	0.641	9.7	
					26.4	0.518	0.696	9.5	
					26.2	0.517	0.642	8.7	
17-178	1% CO_2 + 100 ppm O_2	3.5	1.0	34	29.0	0.525	0.603	9.2	9.1
					28.8	0.522	0.713	10.7	
					29.1	0.517	0.726	11.6	
					28.3	0.530	0.629	9.5	
					29.7	0.541	0.688	11.1	
17-181	0.23% CO_2 + 23 ppm O_2	3.5	4.0	43	29.3	0.546	0.732	11.7	11.1
					29.8	0.537	0.704	11.3	
					30.5	0.542	0.669	11.1	
					29.8	0.546	0.716	11.7	
					29.8	0.546	0.716	11.7	
17-204	Stretched cartridge with gas seal 0.29% CO_2 + 29 ppm O_2	3.5	4.0	36	29.3	0.546	0.732	11.7	11.1
					29.8	0.537	0.704	11.3	
					30.5	0.542	0.669	11.1	
					29.8	0.546	0.716	11.7	
					29.8	0.546	0.716	11.7	

EFG Ribbon Quality: Status

- HIGH SPEED GROWN RIBBON EFFICIENCIES AT 11-12% ARE STILL BELOW BEST EFG RIBBON AVAILABLE, WITH PARTICULAR SHORTFALL IN V_{oc} AND FF.
- ISSUES TO SETTLE:
 - WHAT ARE UNDERLYING MATERIAL QUALITY DEFICIENCIES?
 - CAN THIN RIBBON, PROCESSED WITH IMPROVED GETTERING AND BSF SCHEMES, ACHIEVE GOALS ON PRESENT MATERIAL?

Annealing Studies

- HIGH TEMPERATURE HEAT TREATMENTS (800-1100°C) IN NITROGEN AND OXYGEN AMBIENTS LEAD TO CONSISTENT DEGRADATION OF (DARK) SPV DIFFUSION LENGTHS INDEPENDENTLY OF GROWTH CONDITIONS, INTERSTITIAL OXYGEN LEVEL OF RIBBON (CO_2 ON OR OFF, OR QUARTZ IN THE MELT).
- PH_3 TREATMENT DURING ANNEAL CAN IMPROVE DARK DIFFUSION LENGTH AND APPEARS TO BE NECESSARY TO PRODUCE LIGHT ENHANCEMENT.

LARGE-AREA SILICON SHEET TASK

ORIGINAL PAGE IS
OF POOR QUALITYSchottky Barrier SPV Diffusion Length Measurements Before
and After Heat Treatment of 10 cm Wide Ribbon in an
Oxygen Ambient.

Heat Treatment	Growth Run	Growth Ambient	No. of Sample Pairs	Diffusion Length L_B Before Heat Treat.			Diffusion Length L_A After Heat Treat.			Ratio (L_A/L_B)		
				\bar{x} (μm)	s (μm)	s/\bar{x}	\bar{x} (μm)	s (μm)	s/\bar{x}	\bar{x} (μm)	s (μm)	s/\bar{x}
5 hrs at 800°C in O_2 . Sister sample measurement.	CZ	-	3				83.4	5.42	0.06			
	17-117	argon	8	43.9	21.0	0.48	33.3	7.94	0.24	0.78	0.64	0.65
	17-166	quartz in melt	7	48.7	17.5	0.40	34.3	7.97	0.23	0.78	0.28	0.36
	16-258	0.425 ℓ/min of 1% O_2	8	48.2	21.3	0.44	35.5	15.8	0.44	0.77	0.30	0.39
50 mins at 900°C in O_2 . Sister sample measurement.	CZ	-	3				73.7	15.3	0.21			
	17-117	argon	8	40.6	16.0	0.39	21.6	8.36	0.39	0.57	0.25	0.43
	17-166	quartz in melt	7	43.7	26.5	0.57	30.1	13.1	0.44	0.82	0.65	0.79
	16-258	0.425 ℓ/min of 1% O_2	8	51.0	25.4	0.50	29.0	13.8	0.48	0.60	0.24	0.30
7.5 hrs at 900°C in O_2 . Sister sample measurement.	CZ	-	4	111.0	5.29	0.05	32.6	2.79	0.08	0.294	0.025	0.086
	17-148	argon	6	35.7	8.8	0.25	17.0	9.89	0.58	0.57	0.27	0.48
	17-147	quartz in melt	6	37.2	13.9	0.37	15.7	14.3	0.91	0.41	0.36	0.87

 \bar{x} = mean value; s = standard deviation.Schottky Bar. . SPV Diffusion Length Measurements
Before and After H_2 Diffusion for 10 cm Wide
Ribbon.

Heat Treatment	Growth Run	Growth Ambient	No. of Sample Pairs	Diffusion Length L_B Before Heat Treat.			Diffusion Length L_A After Heat Treat.			Ratio (L_A/L_B)		
				\bar{x} (μm)	s (μm)	s/\bar{x}	\bar{x} (μm)	s (μm)	s/\bar{x}	\bar{x} (μm)	s (μm)	s/\bar{x}
900°C diffusion: 10 mins O_2/N_2 + 30 mins H_2 + furnace cool to 650°C in 100 mins. Same sample measurement.	CZ	-	2	155.0	2.12	0.01	146.0	1.13	0.01	0.94	0.02	0.02
	17-142	argon	7	28.3	12.0	0.42	38.8	11.6	0.30	1.43	0.31	0.22
	17-174	quartz in melt	7	31.3	6.86	0.22	27.6	5.76	0.21	0.88	0.32	0.35
	17-175	0.3% CO_2 + 30 ppm O_2	5	37.7	7.12	0.19	37.5	23.1	0.62	1.11	0.95	0.95
			4	40.3	4.80	0.12	27.9	9.69	0.35	0.70	0.23	0.33
800°C diffusion: 1 hr in O_2/N_2 + 1 hr in H_2 + 4 hrs in O_2/N_2 . Sister sample measurement.	CZ	-	3	157.9	6.77	0.04	116.8	7.74	0.07	0.74	0.57	0.10
	17-117	argon	7	26.5	7.92	0.30	34.9	12.4	0.36	1.40	0.57	0.41
	17-175	0.3% CO_2 + 30 ppm O_2	6	42.8	11.6	0.27	53.3	10.7	0.20	1.33	0.47	0.36
	17-177	1% CO_2 + 100 ppm O_2	8	43.2	7.49	0.17	43.2	10.8	0.25	1.01	0.24	0.23
	17-174	quartz in melt	7	46.4	15.4	0.33	44.3	15.6	0.35	0.96	0.19	0.20

LARGE-AREA SILICON SHEET TASK

Status of EFG Multiple-Ribbon Program: Needs

- NEW FURNACE FOR FOUR 10 cm WIDE RIBBONS IS OPERATIONAL WITH AUTOMATIC WIDTH CONTROL AND MELT REPLENISHMENT. WORK TO BE DONE CONCERNS:
 - ESTABLISHING RELIABILITY, LIFETIME FOR FURNACE COMPONENTS IN LONG TERM OPERATION.
 - IMPLEMENTING AMBIENT CONTROL AT LEVEL WHICH ENSURES QUALITY CONSISTENCY.
- FUNDAMENTAL QUESTIONS REGARDING VIABILITY AND COST-EFFECTIVENESS OF FURNACE IN PRODUCTION MODE REMAIN:
 - YIELDS FOR THIN RIBBON MUST BE HIGH: LOW STRESS, FLATNESS AT 150-200 μ m THICKNESS, 4 cm/min ARE ABSOLUTE NECESSITY.
 - SIMULTANEOUS ACHIEVEMENT OF HIGH DUTY RATE, CONSISTENT QUALITY, HIGH YIELDS MUST OCCUR.

Problems and Concerns

- STRESS AND NON-FLATNESS IN THIN (200 μ m) RIBBON DO NOT PERMIT FABRICATION OF RIBBON GROWN AT HIGHEST SPEEDS (~4 cm/minute) INTO CELLS WITH ACCEPTABLE YIELDS.
- DEMONSTRATE THAT BEST CELL PERFORMANCE LEVELS OF 11-12% ACHIEVED IN SINGLE CARTRIDGE FURNACES CAN BE OBTAINED CONSISTENTLY IN A MULTIPLE RIBBON FURNACE.
- DEMONSTRATE RELIABILITY OF MULTIPLE RIBBON FURNACE OPERATION OVER THE LONG TERM, WITH ACCEPTABLE DUTY RATES, THROUGHPUT AND MATERIAL QUALITY.

SEMICRYSTALLINE PROCESS DEVELOPMENT

SEMIX INC.

TECHNOLOGY LARGE AREA SILICON SHEET	REPORT DATE April 22, 1967
APPROACH SEMICRYSTALLINE CRYSTALLIZATION PROCESS DEVELOPMENT AND VERIFICATION CONTRACTOR SEMIX INCORPORATED	STATUS WORK IS CONTINUING TO DEVELOP AN UNDERSTANDING OF THE BASIC MECHANISMS IN THE CRYSTALLIZATION OF SEMICRYSTALLINE MATERIAL. A TECHNIQUE HAS BEEN DEVELOPED TO DETERMINE BASE RESISTIVITY AND CARRIER LIFETIME IN SEMICRYSTALLINE WAFERS. EXTENSIONS OF THIS TECHNOLOGY ARE BEING PURSUED FOR EVALUATION OF UCP BRICKS. SEMIX HAS ACHIEVED CELLS OF 13.5% EFFICIENCIES IN LIMITED QUANTITIES. WE HAVE COMPLETED THE DESIGN PHASE AND ENTERED THE PROCUREMENT AND CONSTRUCTION PHASE OF A PROTOTYPE 3 UCP SYSTEM CAPABLE OF SOLIDIFYING 42 KILOGRAMS OF SILICON. WE ARE INVESTIGATING THE CRITICAL ELEMENTS NECESSARY TO DEMONSTRATE HIGH THROUGHPUT CAPABILITY.
GOALS INVESTIGATE STRUCTURAL PROPERTIES OF UCP MATERIAL. ASSESS AND DEVELOP TECHNIQUES TO CHARACTERIZE SEMICRYSTALLINE MATERIAL. DEMONSTRATE 14% AMI EFFICIENCY WITH 100 CM ² SOLAR CELLS. EVALUATE AND INVESTIGATE THE CRITICAL ELEMENTS NECESSARY FOR HIGH THROUGHPUT UCP SYSTEMS.	

Principal Areas of Research

- A. FUNDAMENTAL STUDIES OF SEMICRYSTALLINE MATERIAL
- B. HIGH EFFICIENCY SEMICRYSTALLINE SOLAR CELLS
- C. WAFERING MECHANISMS

Areas of Fundamental Study

CRYSTALLIZATION

INVESTIGATION OF THE ROLE OF MICROSTRUCTURE ON THE
PERFORMANCE OF SEMICRYSTALLINE SILICON, MOST NOTABLY
THROUGH:

GRAIN ORIENTATION STUDIES, AND
INVESTIGATION OF STRUCTURAL IN-
HOMOGENEITIES

CHARACTERIZATION

DEVELOPMENT OF TECHNIQUES FOR THE CHARACTERIZATION OF
SEMICRYSTALLINE SILICON FOR BOTH:

RESISTIVITY
CARRIER LIFETIME

Crystallization

PURPOSE: TO DETERMINE THE ROLE OF GRAIN VOLUMES AND GRAIN
BOUNDARIES ON THE QUALITY OF SEMICRYSTALLINE
MATERIAL.

APPROACH: DETERMINATION OF THE RELATIVE ORIENTATION OF NEIGH-
BORING CRYSTALLITES.

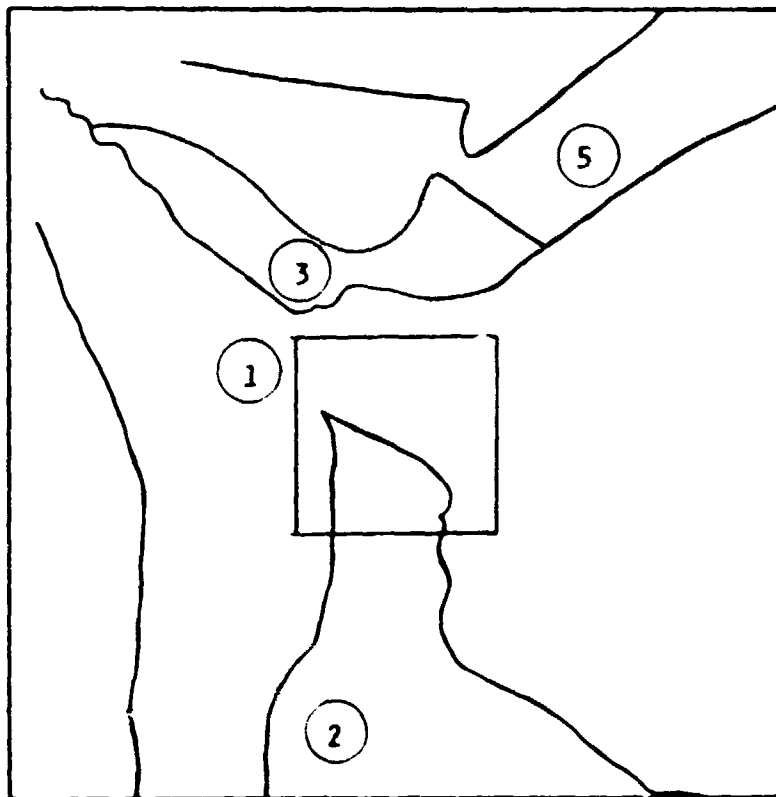
INVESTIGATION OF THE IMPACT OF MICROSTRUCTURAL
DEFECTS ON CELL PROPERTIES:

INDIVIDUAL DISLOCATIONS

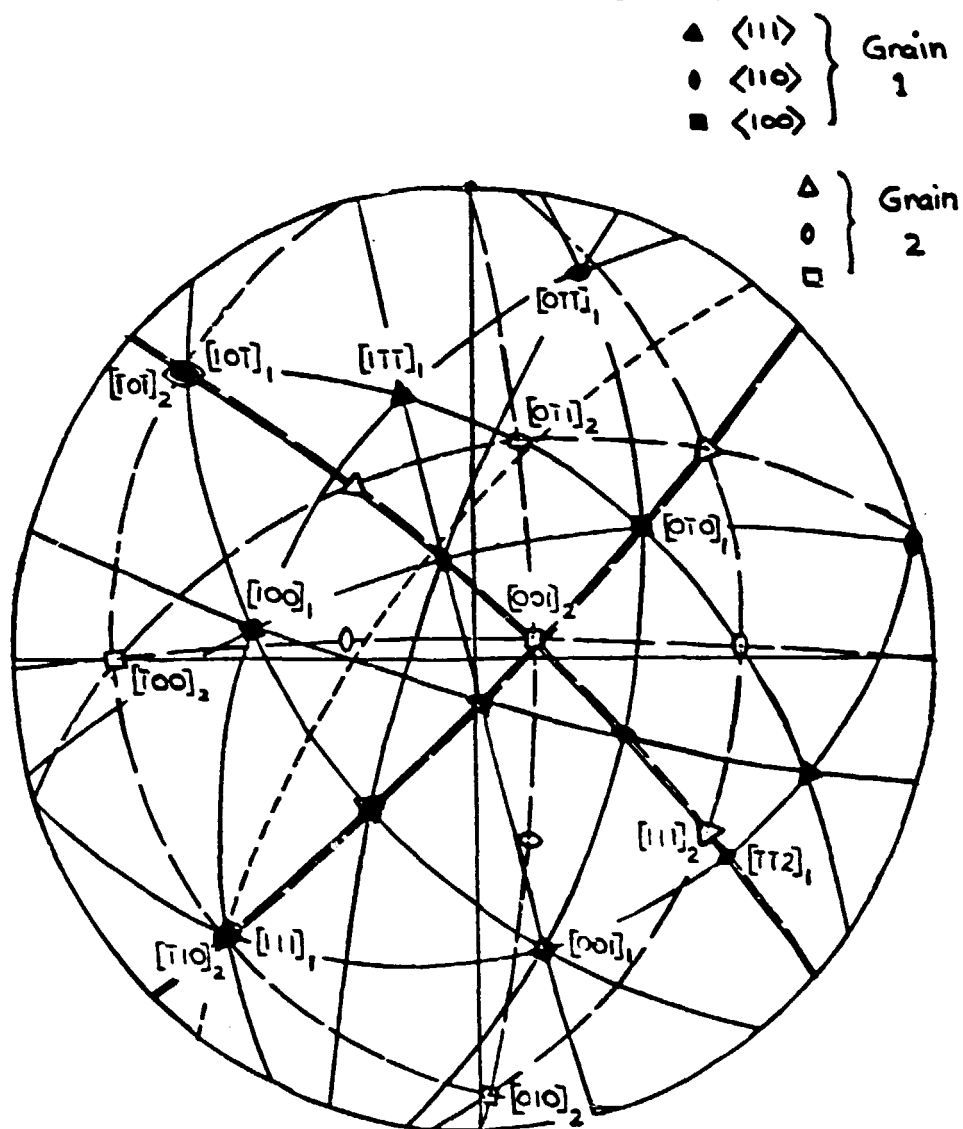
DISLOCATION SUBGRAIN BOUNDARIES

LARGE-AREA SILICON SHEET TASK

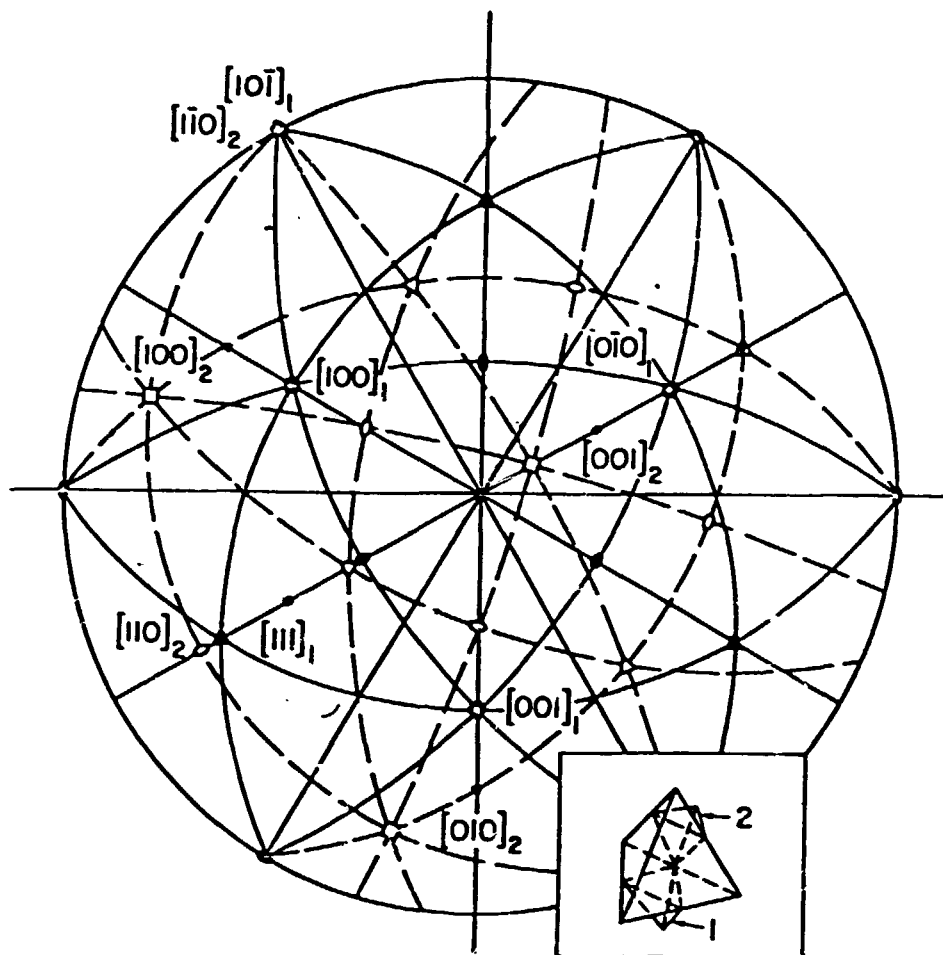
Relative Positions of Grains in Sample Semicrystalline Material



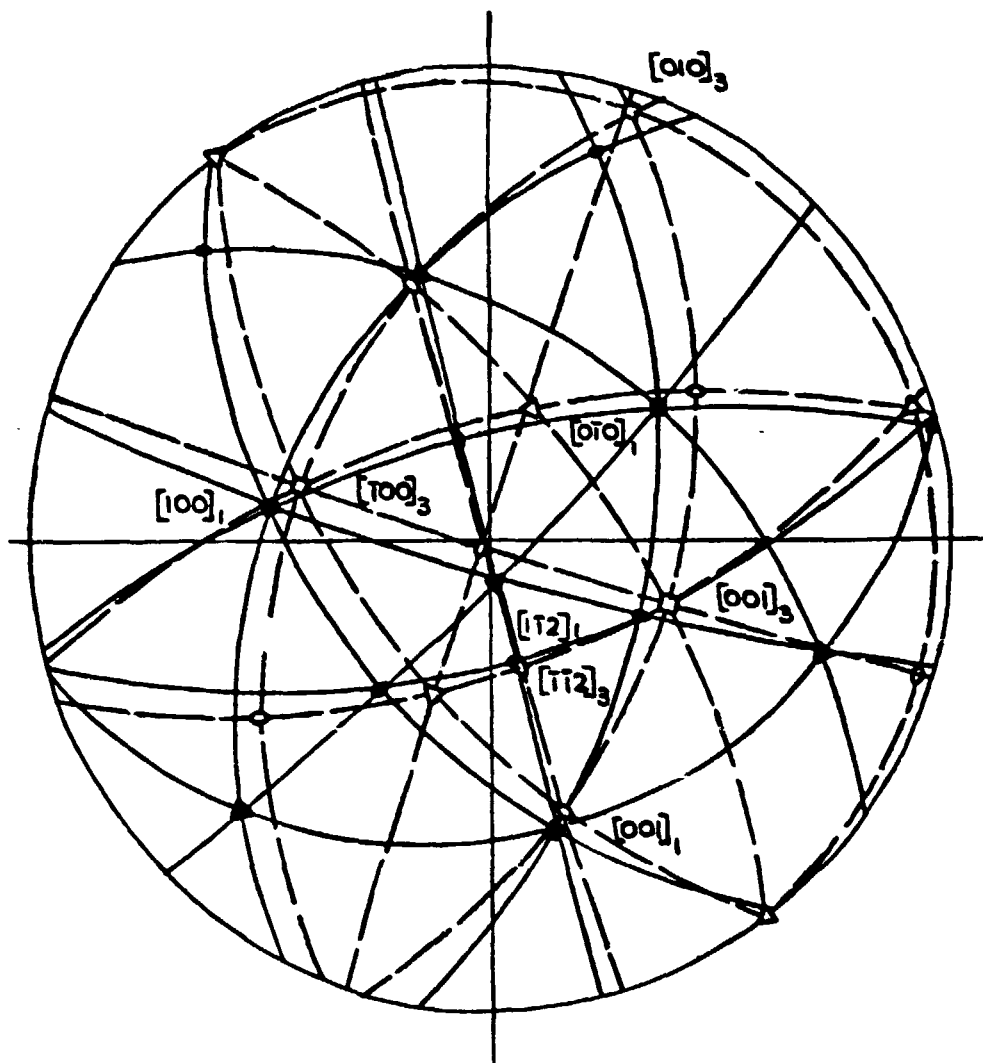
OF POOR QUALITY



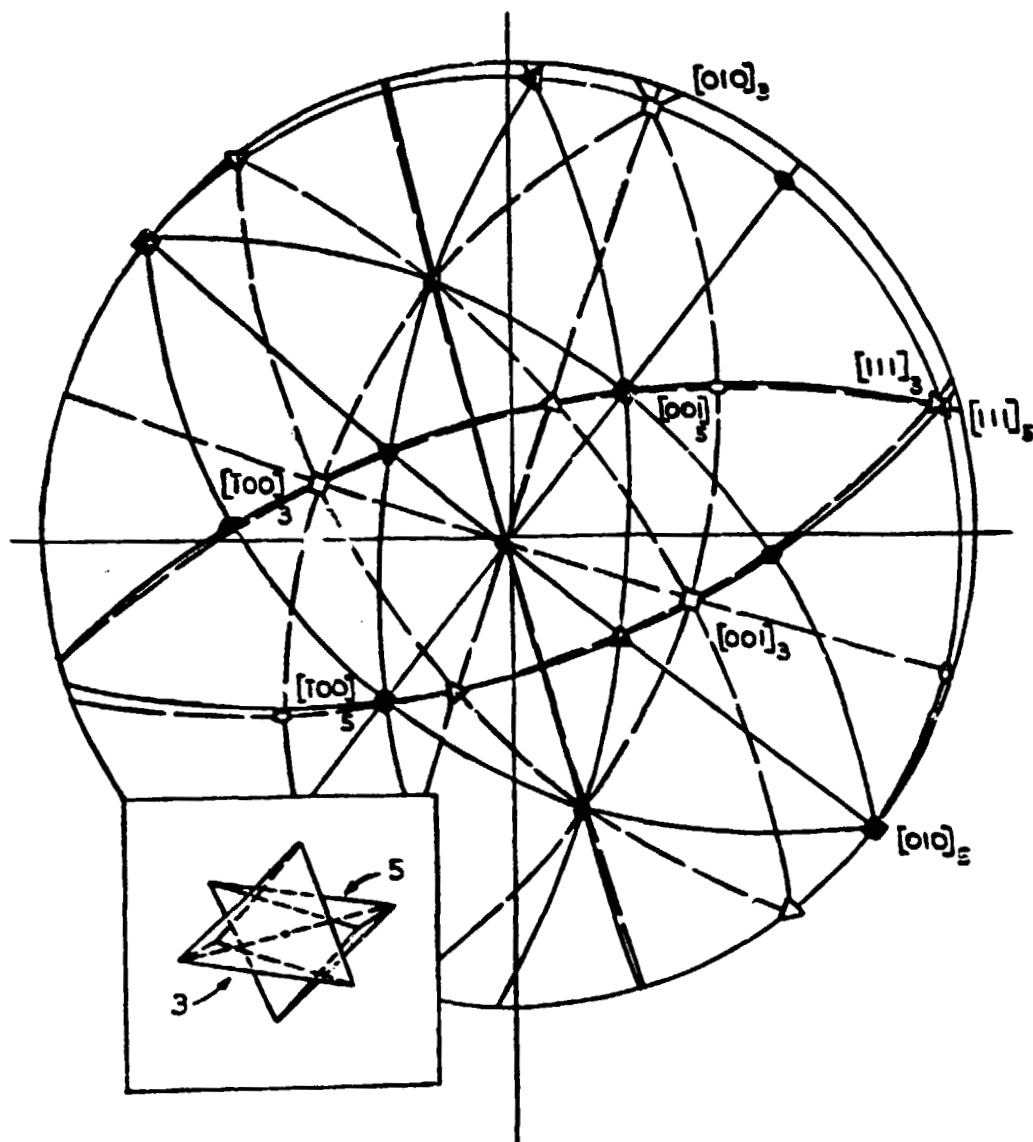
ORIENTATIONS OF GRAINS 1 and 2 IN SAMPLE SEMICRYSTALLINE MATERIAL



Second Order Orientation Relationship of Grains
1 and 2 in {111} Twin Geometry Relative to a Third
Grain



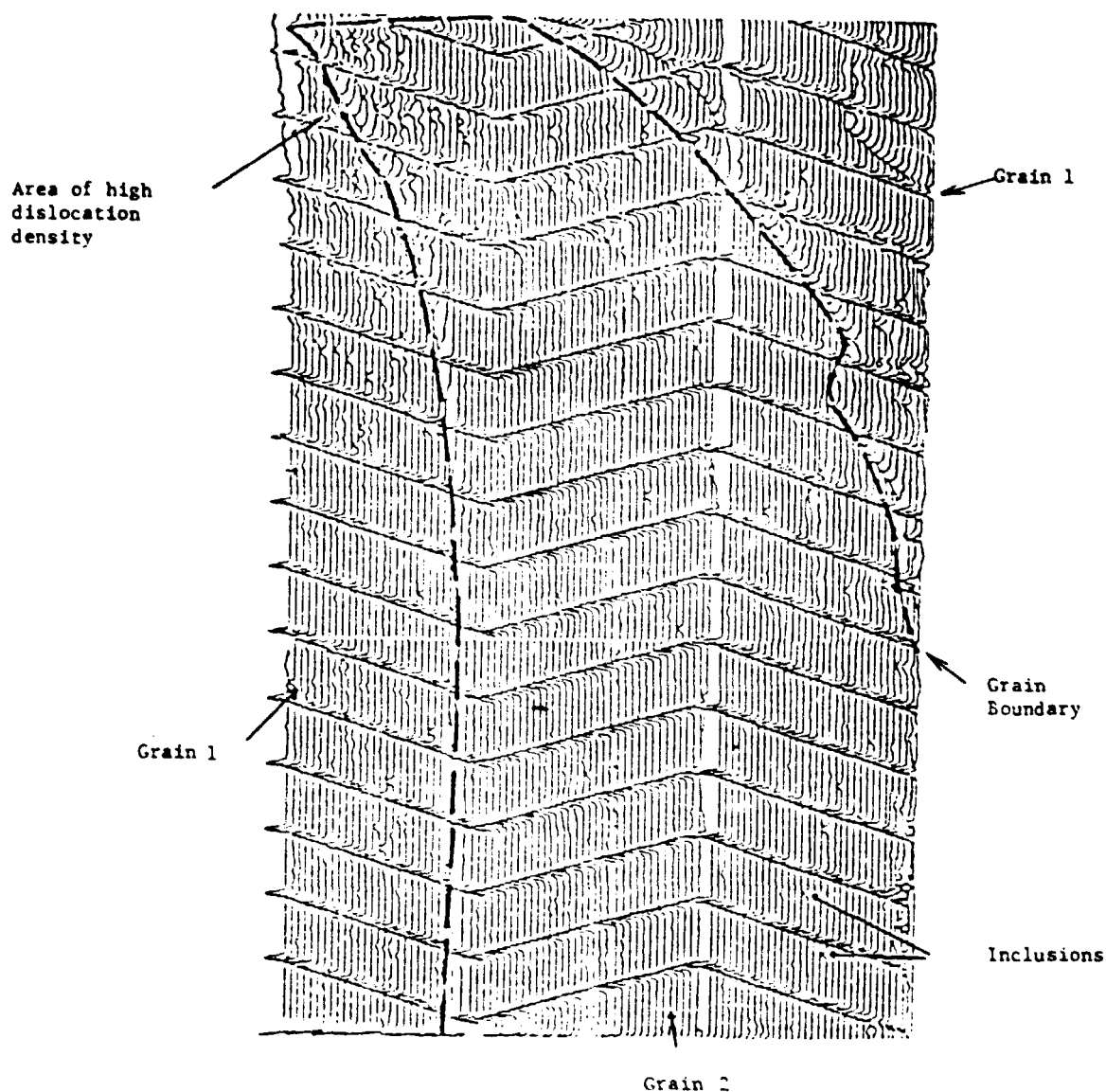
Orientation Relationship for Grains 1 and 3 of 90°
Rotation About Nearly Common $\langle 112 \rangle$ Axes



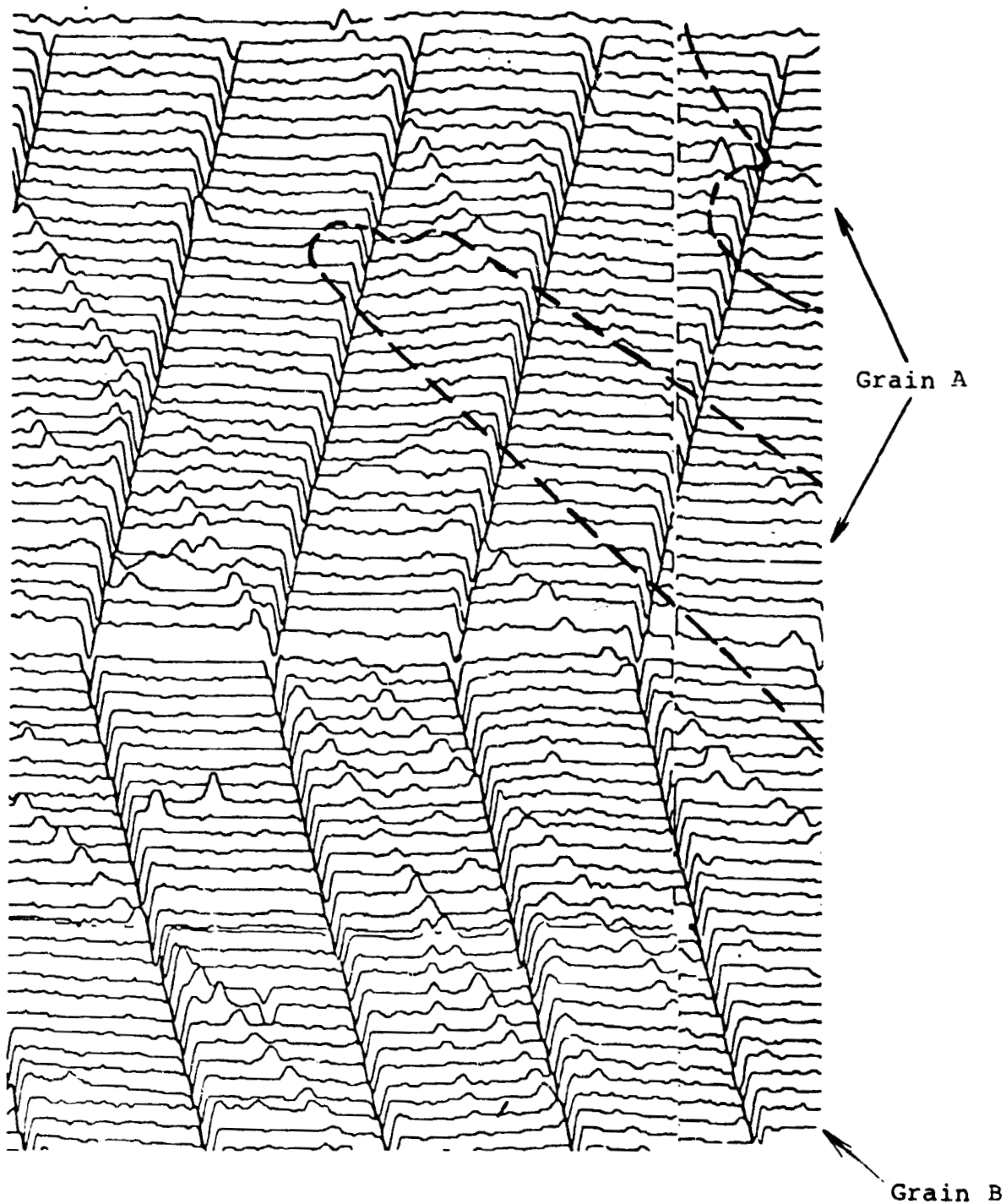
(111) Twin Orientation Relationship of Grains 3 and 5

LARGE-AREA SILICON SHEET TASK

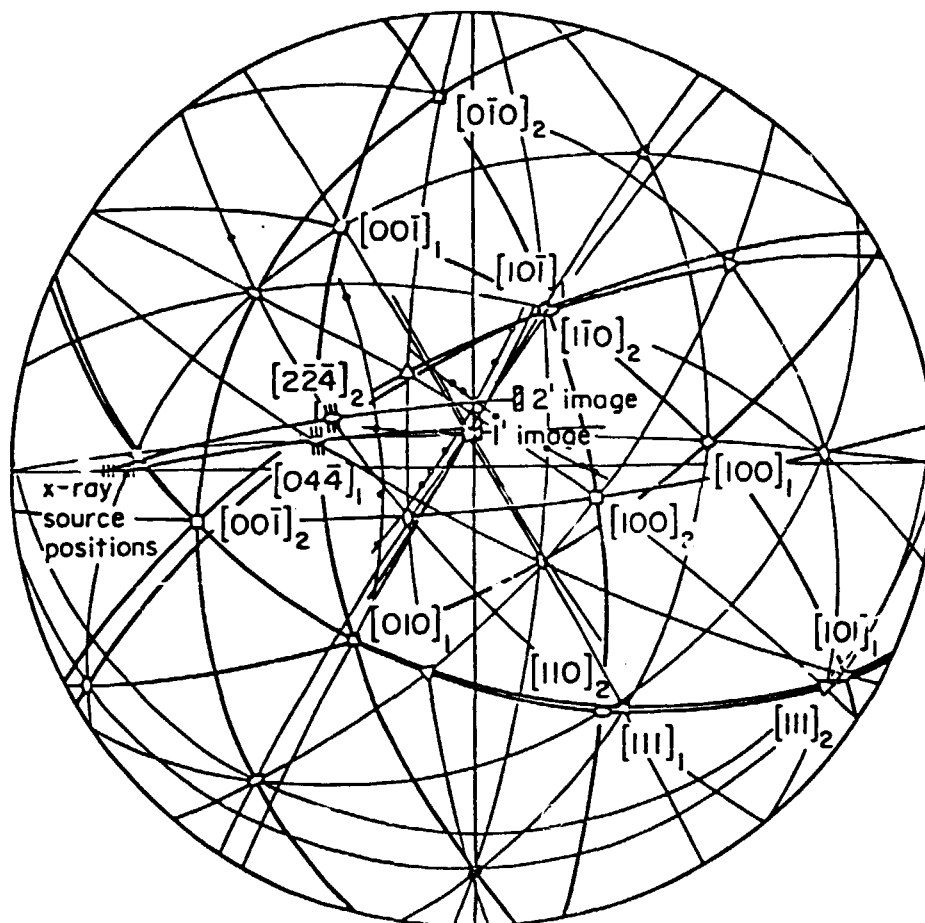
ORIGINAL FACE IS
OF POOR QUALITY



Scanning Photoresponse Pattern of an Area of a 2cm x 2cm
13% AM1 Efficient Cell Showing the Location of the Grain
Boundaries and an Area of High Dislocation Density



Scanning Photoreponse Pattern of an Area of a
2cm. x 2cm. Cell, No. 4726-C3-4, Including the Location
of the Electrically Inactive Grain Boundaries



Second Order Twin Relationship of Grains 1 and 2
Oriented to Give $(044)_1$ and $(224)_2$ Skew Reflections

Conclusions

IN UCP SEMICRYSTALLINE SILICON, MOST GRAIN ORIENTATIONS APPEAR TO BE CRYSTALLOGRAPHICALLY RELATED BY A MULTIPLE ORDER TWINNING RELATIONSHIP, AND MOST GRAIN BOUNDARY INTERFACES ARE CRYSTALLOGRAPHICALLY DETERMINED. AS LONG AS THE CRYSTALLOGRAPHICALLY DETERMINED BOUNDARIES CONTAIN NO DISLOCATIONS, THE BOUNDARIES SHOW NO DELETERIOUS ELECTRICAL BEHAVIOR.

BECAUSE OF THE LARGE GRAIN SIZE OF THIS MATERIAL, AND THE LOW DENSITY OF NON-CRYSTALLOGRAPHICALLY RELATED BOUNDARIES, GRAIN BOUNDARIES HAVE A MINIMAL EFFECT ON THE PHOTOVOLTAIC PROPERTIES OF SEMICRYSTALLINE SILICON.

MINIMIZING INTERNAL GRAIN DEFECTS THEN BECOMES THE KEY TO HIGH WAFER QUALITY.

THE INTERNAL GRAIN ORDER IS AFFECTED BY MANY FACTORS INCLUDING:

- INCLUSIONS
- INDIVIDUAL DISLOCATIONS
- IMPURITIES
- DISLOCATION SUBGRAIN BOUNDARIES

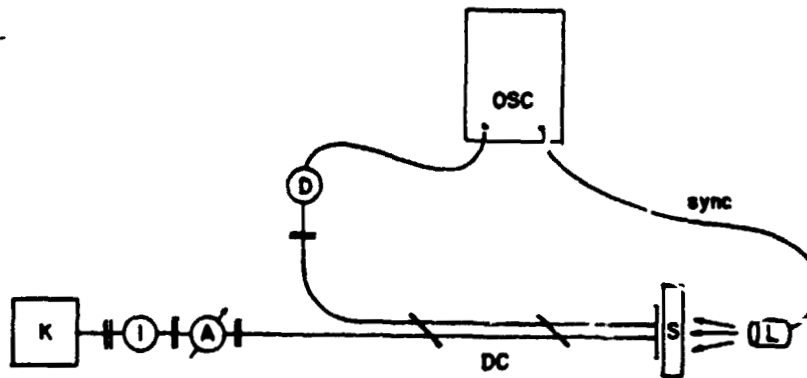
OCCASIONALLY, THE LARGE CRYSTAL WILL DEVELOP A SUBGRAIN DEFECT STRUCTURE. THIS STRUCTURE IS COMPRISED OF NUMEROUS SUBGRAINS THAT HAVE GRAIN DIAMETERS ON THE ORDER OF ONE MILLIMETER OR LESS AND APPEAR TO BE ROTATED BY 5° - 7° ABOUT SPECIFIC CRYSTALLOGRAPHIC DIRECTIONS SUCH AS A $\langle 110 \rangle$ AXIS.

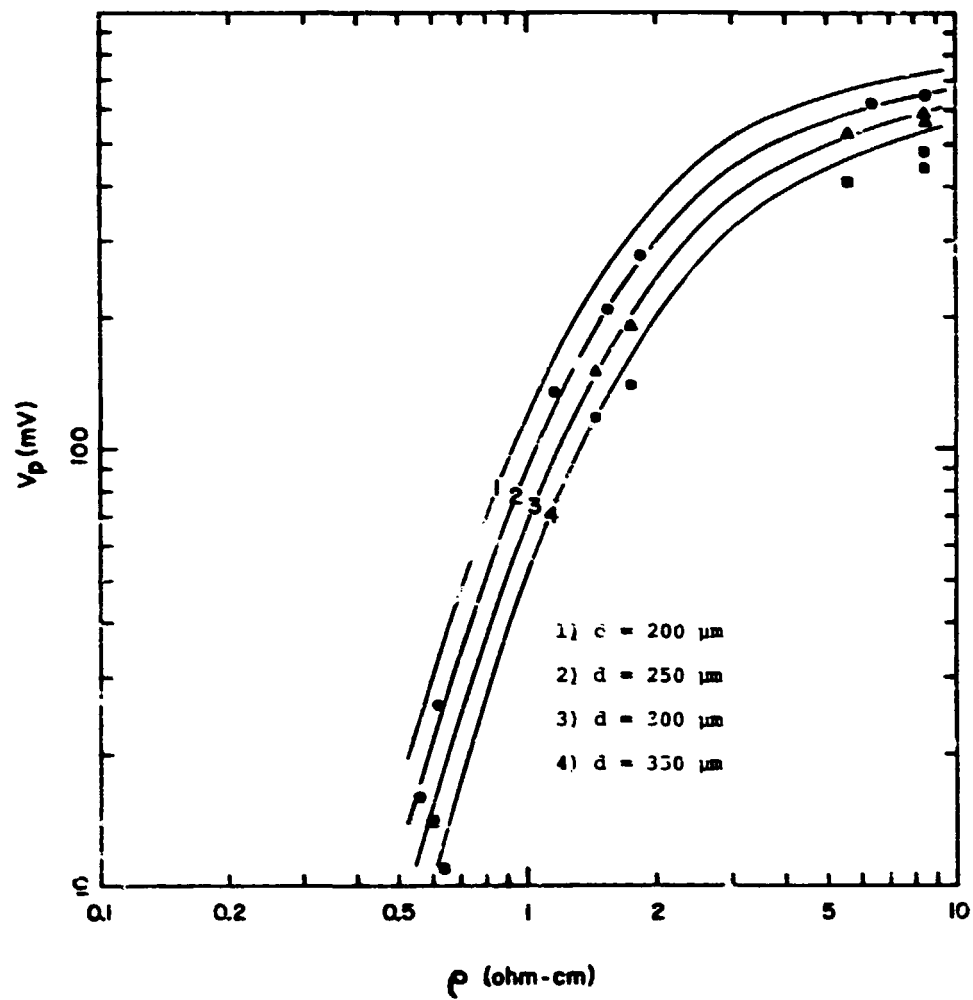
Determination of Lifetimes in Semicrystalline Si

PURPOSE:

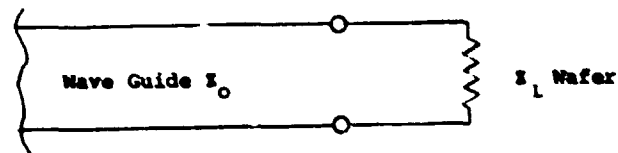
DEVELOP A CONTACTLESS TECHNIQUE FOR THE MEASUREMENT
OF CARRIER LIFETIMES IN SEMICRYSTALLINE MATERIAL.

UNIQUENESS OF APPROACH:



Variation in Measured Response vs Base
Resistivity and Sample Thickness

Theoretical Model



ASSUMPTIONS

High Conductivity Limit

$$\sigma \gg \omega \epsilon$$

Exponential Carrier Distribution

No Diffusion of Carriers

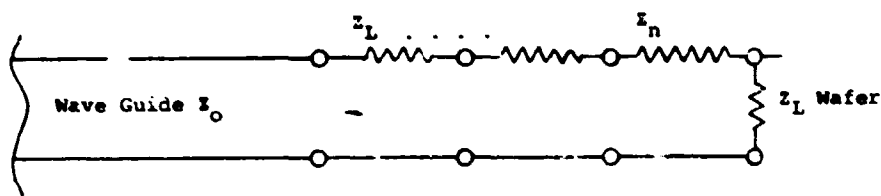
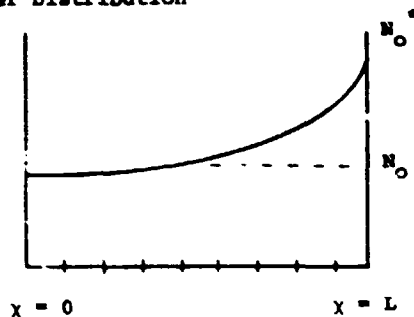
No Surface Recombination Velocity

Carriers Decay Exponentially with Time

$$N(t) = N_0 e^{-t/\tau}$$

Transmission-Line Model

Carrier Distribution



Reflection Coefficient

$$R = \frac{Z_L - Z_0}{Z_L + Z_0} \quad ; \quad R \ll N_0 + N_0^*$$

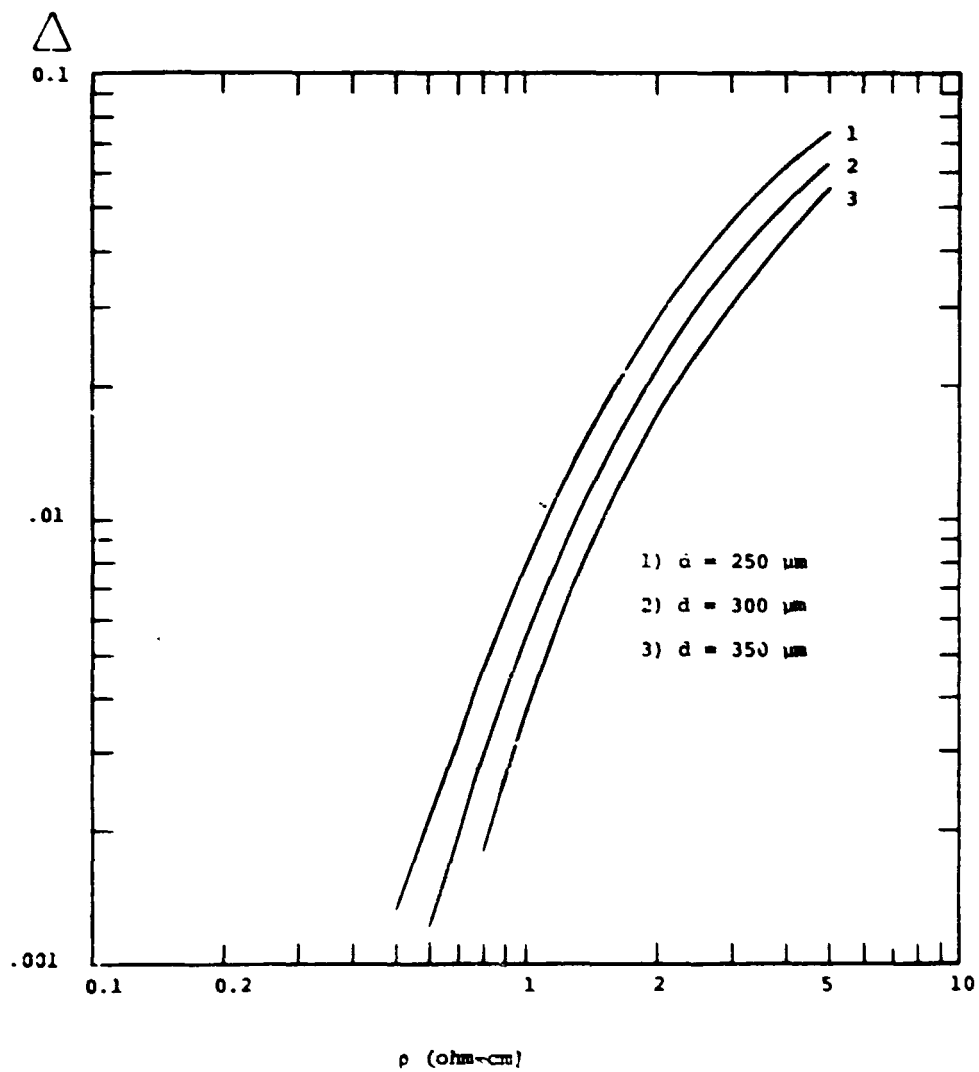
Reflected Power

$$P_M = RR^* \ll V_M$$

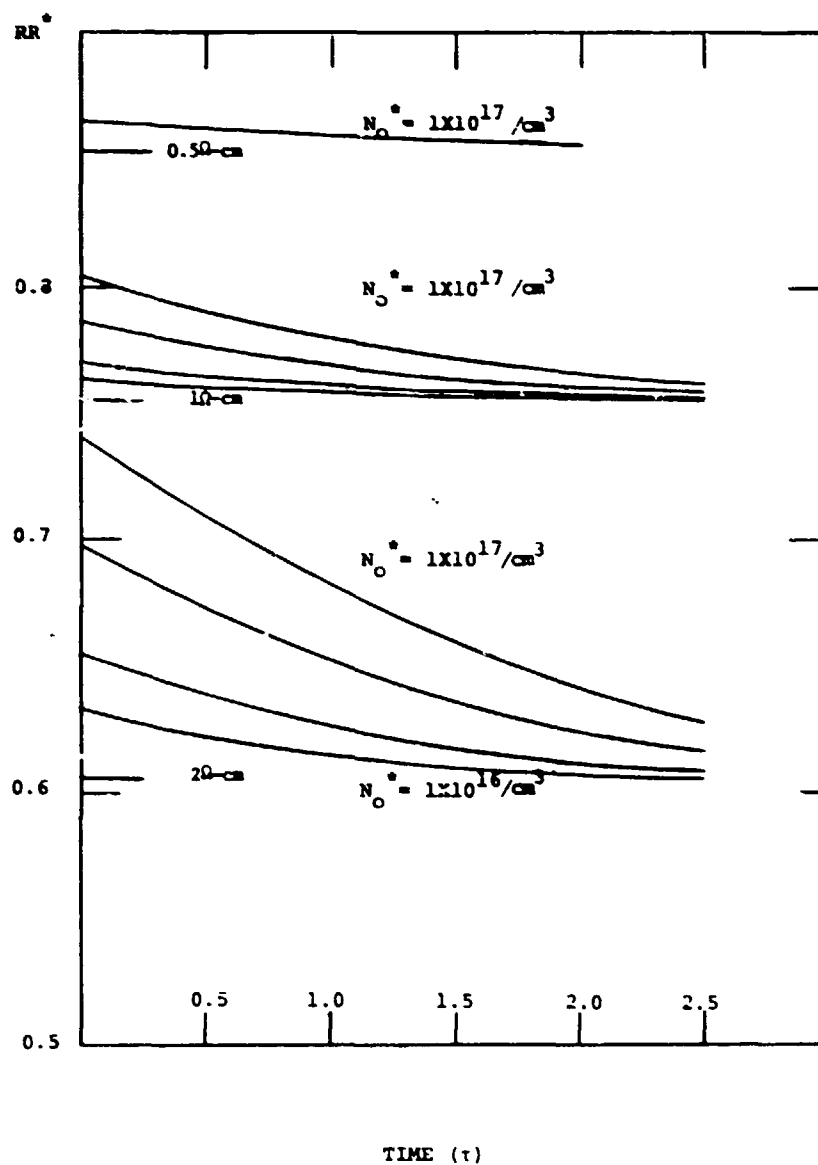
Normalized Modulation

$$\Delta = \frac{V_M^* - V_M}{V_H}$$

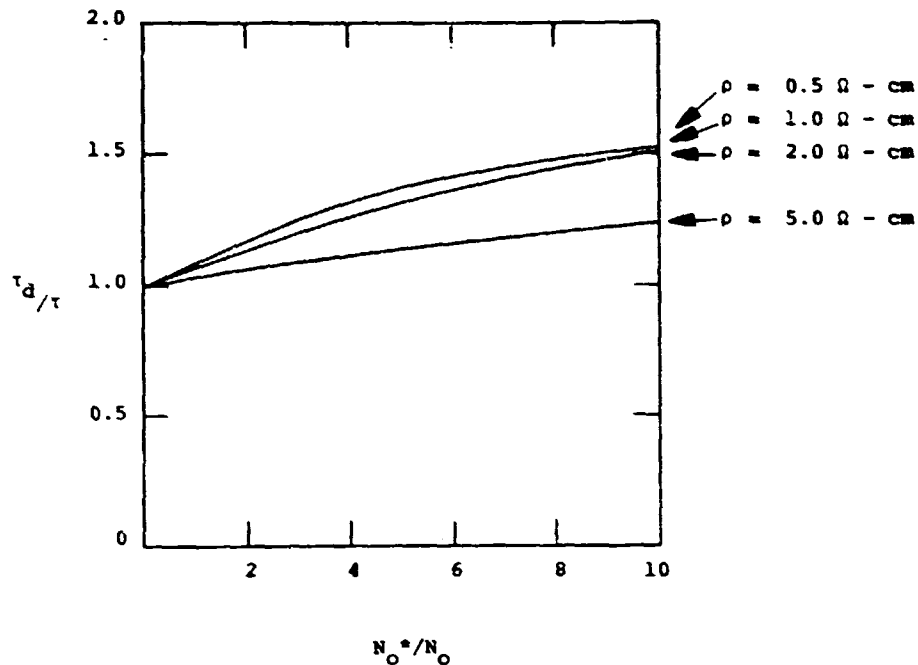
Normalized Modulation Calculated vs Base Resistivity and Sample Thickness



Change in Reflected Power With Time



Variation in Measured Decay Time vs Base Resistivity and Generated Carrier Concentration



Conclusions

THIS IS A RELIABLE TECHNIQUE FOR THE CHARACTERIZATION OF SEMI-CRYSTALLINE MATERIAL. THE MODEL ACCURATELY PREDICTS THE OBSERVED BEHAVIOR ASSOCIATED WITH CHANGES IN BASE RESISTIVITY AND SUBSTANTIATES THE EMPIRICALLY OBSERVED BEHAVIOR FOR THE PREDICTION OF CARRIER LIFETIMES.

SURFACE PASSIVATION IS NECESSARY TO OBTAIN CONSISTENT AND MEANINGFUL RESULTS.

THE MEASURED DECAY TIME IS SOME MULTIPLE OF THE CARRIER LIFETIME, DEPENDENT UPON THE:

SAMPLE THICKNESS
BASE RESISTIVITY
ILLUMINATION INTENSITY

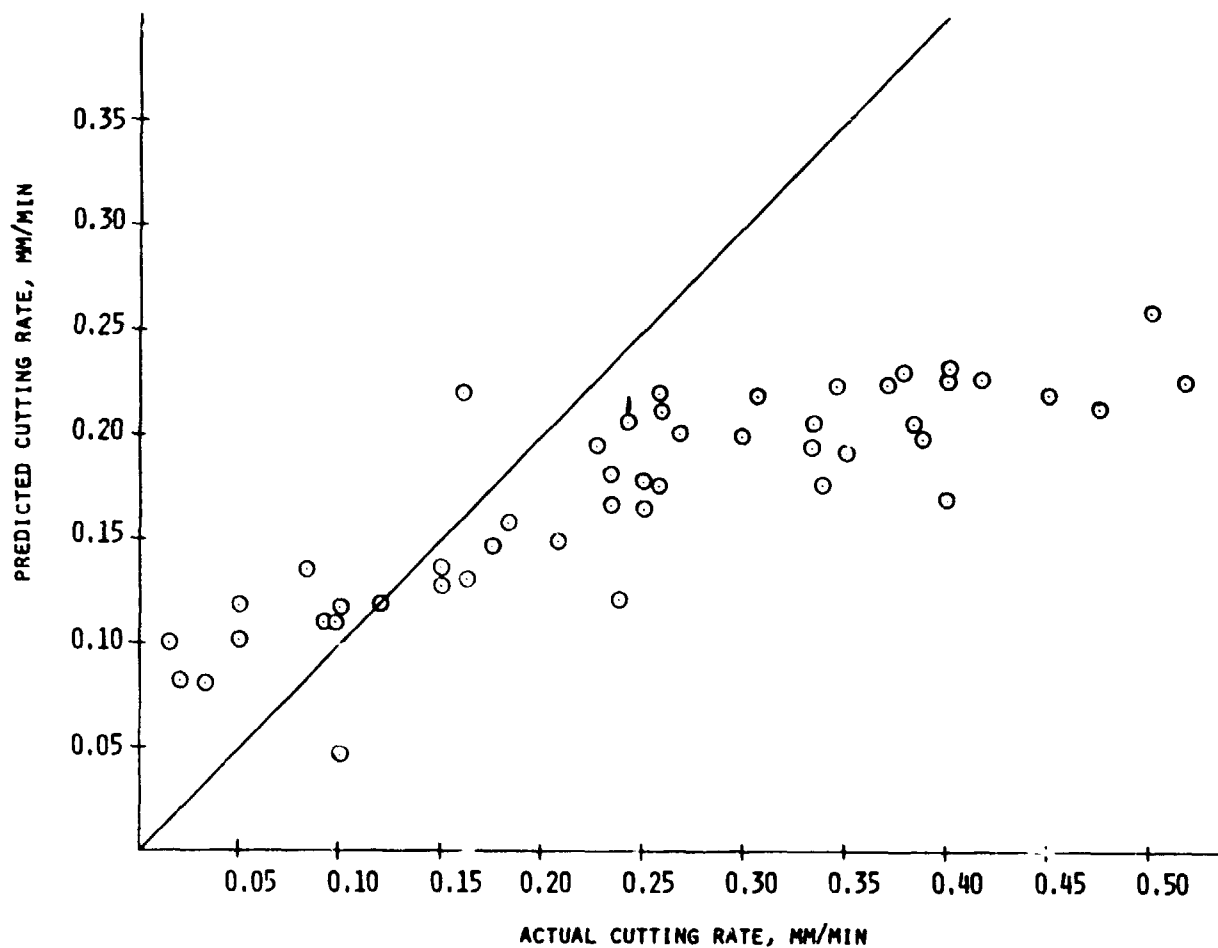
LARGE-AREA SILICON SHEET TASK

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Wafering Mechanisms

PURPOSE: TO DETERMINE IF THE HSMBS WAFERING TECHNOLOGY IS A
VIABLE METHOD FOR THE ECONOMICAL PRODUCTION OF SHEET
SILICON FOR PHOTOVOLTAICS.

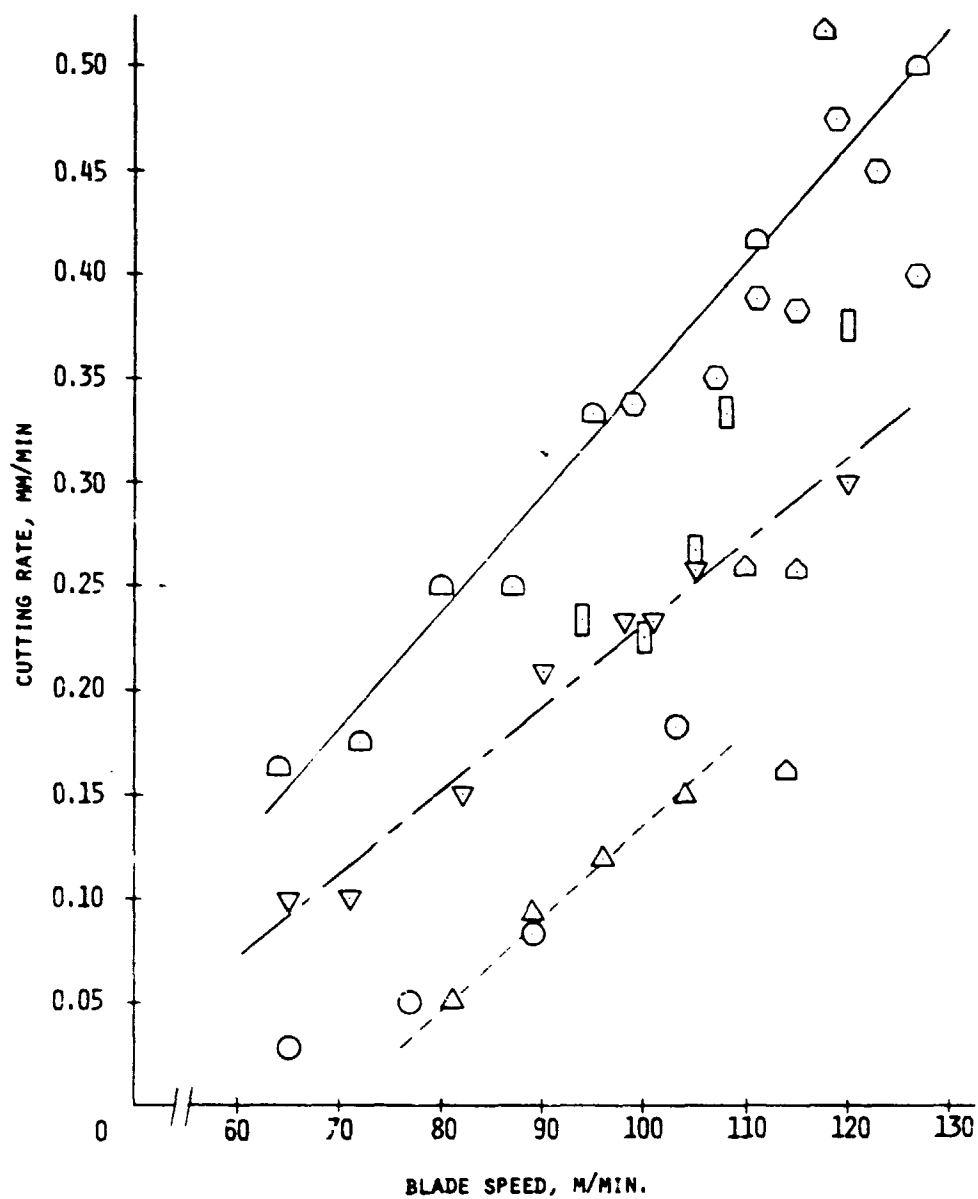
High-Speed MBS Saw

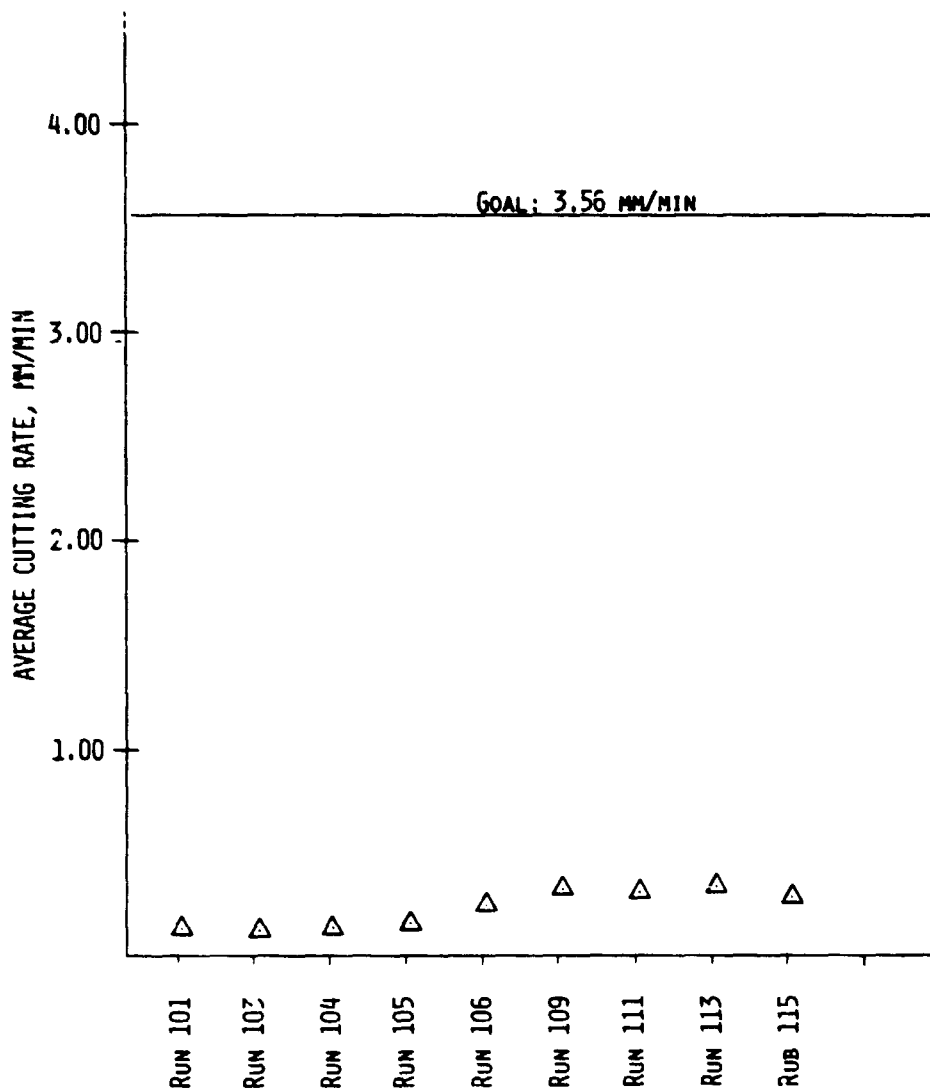


LARGE-AREA SILICON SHEET TASK

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High-Speed MBS Saw: Cutting Rate vs Blade Speed



High-Speed MBS Saw: Average Cutting Rates
(Complete Runs Only)

Conclusions

WITH THE HIGH MATERIALS COST ASSOCIATED WITH THE MBS TECHNOLOGY A CUTTING RATE OF $1\text{ m}^2/\text{HR.}$ IS NECESSARY.

BASED UPON THE RESEARCH PERFORMED THUS FAR, IT WOULD BE NECESSARY TO SUSTAIN A CUTTING RATE OF 3.5 MM/MIN.

THE CURRENT TECHNOLOGY IS NOT CAPABLE OF MEETING THIS CRITERIA.

ADVANCED CZOCHRALSKI INGOT GROWTH

KAYEX CORP.

ADVANCED CZOCHRALSKI INGOT GROWTH	KAYEX CORPORATION APRIL 22, 1982
GOALS:	STATUS:
GROWTH OF 150 KG OF INGOTS FROM ONE CRUCIBLE USING PERIODIC MELT REPLENISHMENT	ONE 150 KG RUN PERFORMED DURING THIS CONTRACT
DIAMETER 15 CM	ACHIEVED
THROUGHPUT - 2.5 KG/HR	1.46 KG/HR, 150 KG RUN
RECHARGE MELTING RATE 25 KG/HR	14.3 KG/HR
AFTER-GROWTH YIELD 90%	ACHIEVED; 52% MONO, BALANCE POLY
MICROPROCESSOR CONTROLS PLUS IMPROVED SENSORS FOR:	CONSTRUCTED, INTERFACED & DEMONSTRATED
MELT TEMPERATURE	
DIAMETER	
MELT LEVEL	
PROTOTYPE EQUIPMENT FOR HIGH VOLUME PRODUCTION, TRANSFERABLE TO INDUSTRY	JPL MOD 2000 → CG6000
	RL 4/22/82

LARGE-AREA SILICON SHEET TASK

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ADVANCED CZOCHRALSKI
INGOT GROWTH

KAYEX CORPORATION
APRIL 22, 1982

APPROACH:

CONSTRUCT AN IMPROVED CRYSTAL
GROWER HAVING THE PERFORMANCE
REQUIRED TO ACHIEVE GOALS

CONSTRUCT AN AUTOMATED SYSTEM
WHICH WILL OFFER RELIABLE
PERFORMANCE LEADING TO IMPROVED
YIELDS AND REDUCED LABOR COST

CONDUCT PROCESS DEVELOPMENT ON
LARGE SIZE CRYSTAL GROWTH, MELT
REPLENISHMENT AND IMPROVED
THROUGHPUT AND YIELDS

CONDUCT PARALLEL ANALYTICAL PROGRAM
TO HELP UNDERSTAND THE PROCESS

STATUS:

INGOT SIZE ACHIEVED, BUT NOT
THROUGHPUT

SYSTEM OPERATIONAL - INSUFFICIENT
DATA TO CONFIRM YIELD & LABOR

INGOT SIZE 6" DIA x 37-1/2 KG
ACHIEVED
THROUGHPUT BELOW TARGET

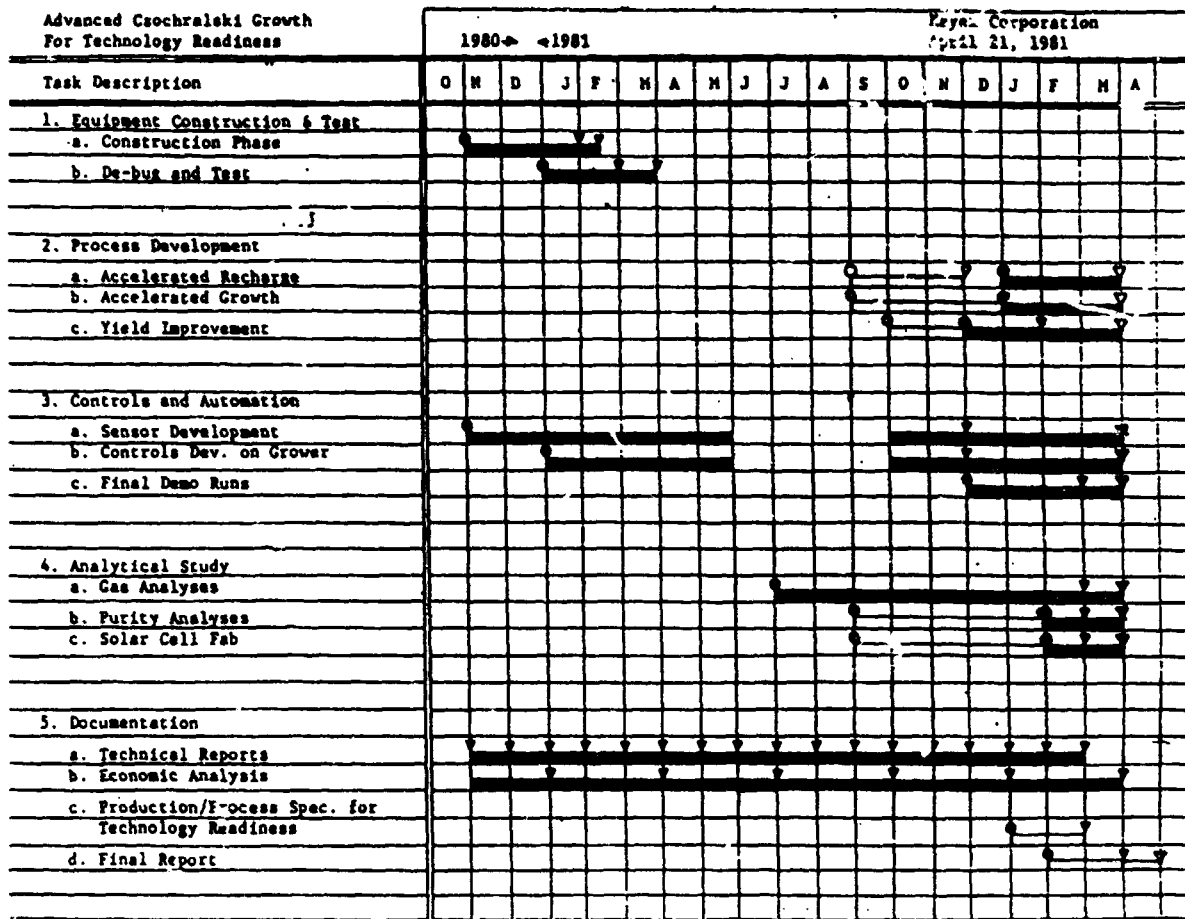
FURNACE GAS ANALYSES
CRUCIBLE DEVITRIFICATION STUDY
SOLAR CELL FAB AND TEST

RLL 4/22/82

LARGE-AREA SILICON SHEET TASK

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Program Plan, Revision 2



Program Plan

THE PROGRAM PLAN CONSISTS OF, FIRST, A CONSTRUCTION PHASE, WHICH WAS COMPLETED IN THE FIRST FIVE MONTHS.

A PARALLEL SENSOR DEVELOPMENT PROGRAM WAS CARRIED OUT INITIALLY ON A SECOND COMMERCIAL MACHINE AND, SUBSEQUENTLY, THE SENSORS WERE INTERFACED TO THE JPL FACILITY.

FOR A PERIOD OF TIME IN LATE 1981, VERY LITTLE EFFORT WAS EXPENDED, EXCEPT FOR THE CONTINUED DEVELOPMENT OF THE GAS ANALYSIS SYSTEM.

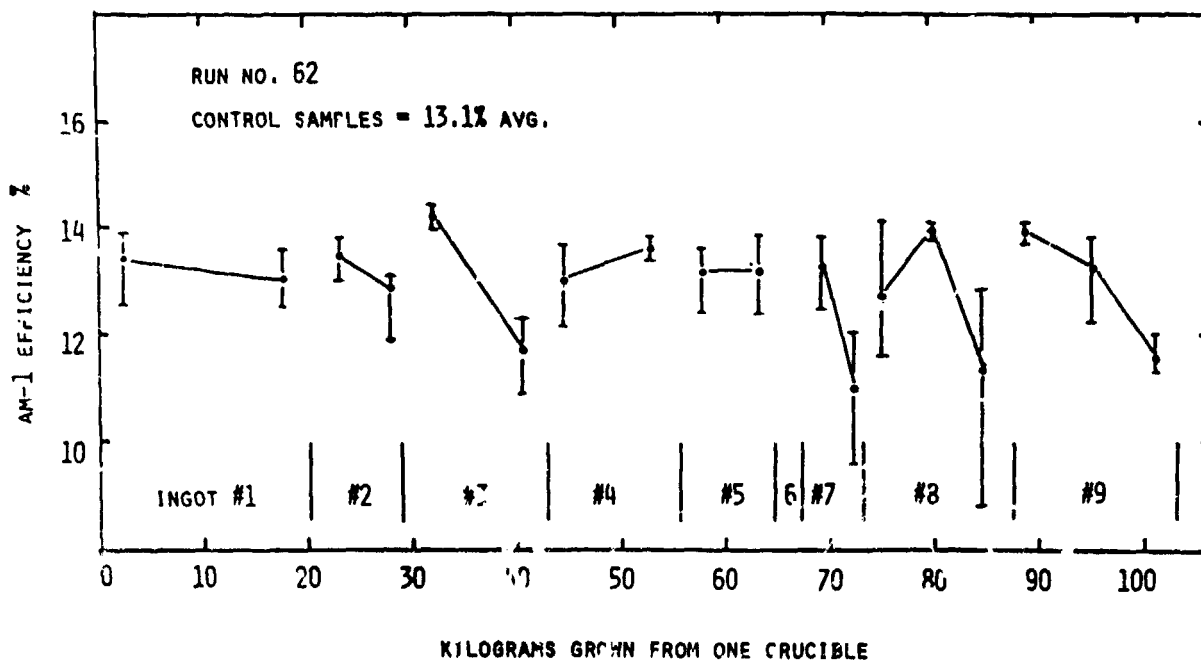
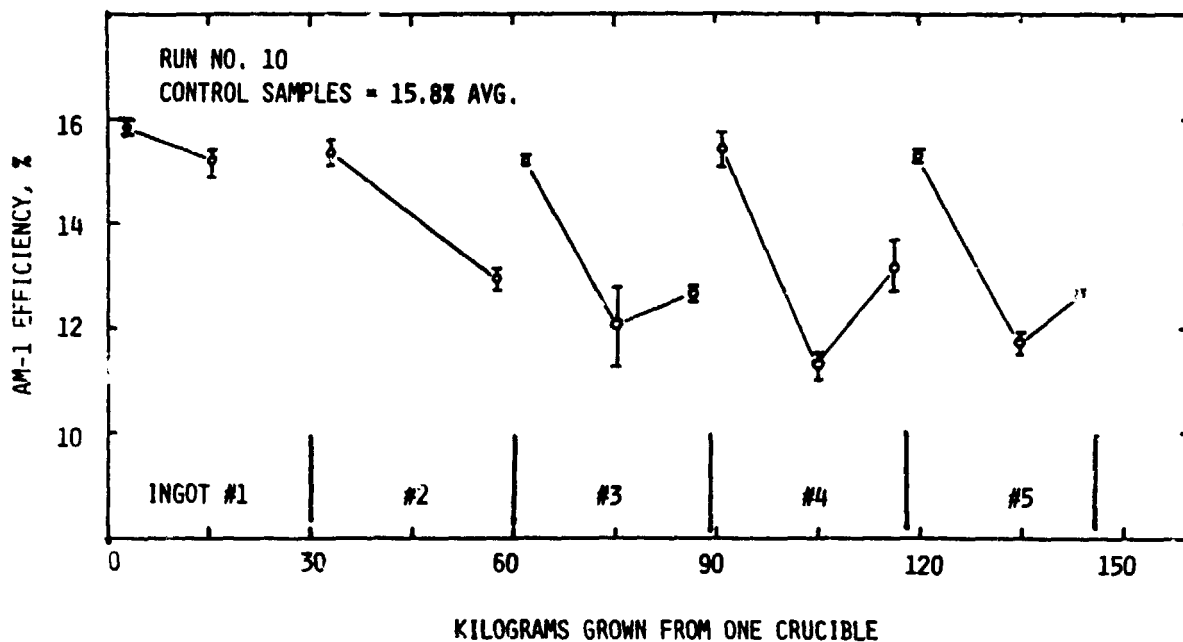
FOR THE LAST SEVERAL MONTHS, THE EFFORT WAS REDIRECTED THROUGH A TDM TO EMPHASIZE PROCESS UNDERSTANDING RATHER THAN EXTENSIVE DEMONSTRATION OF 150 KG RUNS.

THE EXPERIMENTAL WORK IS NOW COMPLETE AND THE FINAL DOCUMENTATION IS IN PROCESS.

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Solar Efficiency vs Kilograms Grown



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ADVANCED CZOCHRALSKI INGOT GROWTH		KAYEX CORPORATION DOE/JPL 955733	
PROBLEMS - CONCERNS			
<u>PROBLEM AREA</u>		<u>APPROACH</u>	
● YIELD OF MONOCRYSTAL, LOWER EFFICIENCY OF POLY MATERIAL		● STUDY STRUCTURE LOSS MECHANISMS, PRIMARY MELT CONTAMINATION	
		- CRUCIBLE DISSOLUTION	
		- CRUCIBLE DEVITRIFICATION	
		- GAS AMBIENT PURITY & FLOW	
● THROUGHPUT IS RELATED TO RATE LIMITING FACTORS		● IMPROVE HOT ZONE DESIGN	
- MELTING RATE		- FURTHER WORK WITH RADIATION SHIELDING	
- CORKSCREWING		- TEMPERATURE PROFILING OF MELT	
- STABILIZATION OF MELT TEMPERATURE		- IMPROVED TUNING OF MICROPROCES- SOR TO SPEED UP STABILIZATION, SEEDING AND NECKING	

ADVANCED CZOCHRALSKI ENERGY DISPERSIVE X-RAY ANALYSIS OF ROSETTE DEFECTS ON INNER SURFACE OF USED CRUCIBLE				
1. COMPOSITION AT RIM OF DEFECT				
<u>ELEMENT</u>	<u>ATOMIC WEIGHT PERCENT</u>	<u>ATOMIC PERCENT</u>	<u>OXIDE FORMULA</u>	<u>OXIDE PERCENT</u>
SI	87.39	89.92	SiO ₂	91.53
S	1.97	1.78	SO ₃	2.52
CL	6.15	5.01	CL	3.11
K	2.91	2.15	K ₂ O	1.75
CA	1.58	1.14	CAO	1.09
2. COMPOSITION OF CENTER OF DEFECT AND BULK SiO ₂ GLASS CONTAINED NO DETECTABLE IMPURITIES.				
RLI 4/21/82				

LARGE-AREA SILICON SHEET TASK

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CO and H₂ vs Run Time

IN AN ATTEMPT TO UNDERSTAND THE MECHANISM OF STRUCTURE LOSS, WE HAVE CONSTRUCTED A DEVICE WHICH SAMPLES AND ANALYZES THE GROWER EXHAUST GAS FOR CARBON MONOXIDE, HYDROGEN, AND WATER. IF CARBON IS CONTAMINATING THE MELT, IT WILL BE CONCENTRATED IN THE RESIDUAL MELT AND COULD LEAD SUBSEQUENTLY TO SILICON CARBIDE PRECIPITATION, AS MORE AND MORE CRYSTALS ARE GROWN.

CARBON MONOXIDE HAS BEEN FOUND IN SURPRISINGLY HIGH CONCENTRATIONS, AND IS A FUNCTION OF TEMPERATURE. APPROXIMATELY 5000 PPM ARE SEEN DURING MELTDOWN.

LARGE-AREA SILICON SHEET TASK

MATERIAL CHARACTERIZATION

CORNELL UNIVERSITY

<p>TECHNOLOGY</p> <p>LARGE AREA SILICON SHEET - ANALYSIS</p>	<p>REPORT DATE</p> <p>April 17, 1982</p>
<p>APPROACH</p> <ul style="list-style-type: none"> • Optical Microscopy and Etching. • Transmission Electron Microscopy • Electron beam Induced Current Microscopy • Chemical Analysis (e^-, ion, neutron, mass spec). <p>CONTRACTOR</p> <p>Cornell University/Material Science</p>	<p>STATUS</p> <ul style="list-style-type: none"> • EFG TEM and STEM analysis of defects in processed EFG completed. Chemical make up of large precipitates identified. • WEB RT EBIC of processed WEB completed. Temperature dependent EBIC being carried out to determine local energy levels. Rutherford backscattering completed. • HEM Optical Microscopy and etching completed EBIC completed. • <u>NEW ANALYTICAL TOOLS ADDED SINCE LAST PI</u>
<p>GOALS</p> <ul style="list-style-type: none"> • Characterize structure and chemical composition of point, line and planar defects in un-processed LASS material. • Characterize structure and chemical composition of point, line and planar defects in processed LASS material. • Evaluate crystal growth/defect relation • Evaluate processing/defect relation. 	<ul style="list-style-type: none"> 1) JEOL 200 CX STEM with EDX 2) Temperature dependent EBIC 3) General Ionix Accelerator for back-scattering analysis.

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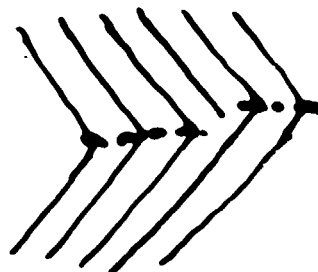
Coherent Twins

- 60° rotation on (111) plane
 - perfect first nearest neighbor fit
- Periodicity of three
 - SIGMA 3 boundary
- Small deviations from ideal twin are accomodated by DSC dislocations

$b = (a/6) 112$

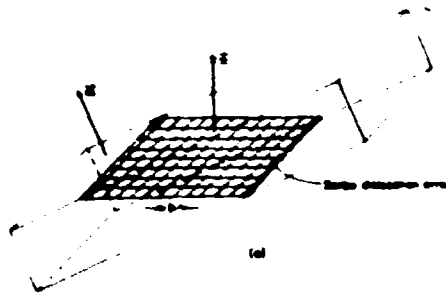
These dislocations are the analogue of complete dislocations in small angle grain boundaries.
- Dislocations are necessarily associated with a step in the boundary
 - presents possibility to study effects of jogs.

C C C C C
 B B B A A
 A A A B B
 C C C C C
 B B B B B
 A A A A A

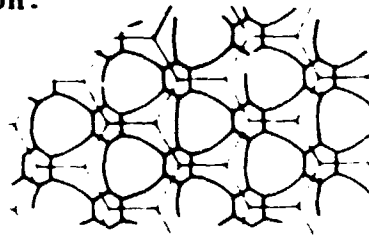


Twist Boundaries

Network of screw dislocations



On (111) dislocations react to form
hexagonal networks - low angle - twin
relation.



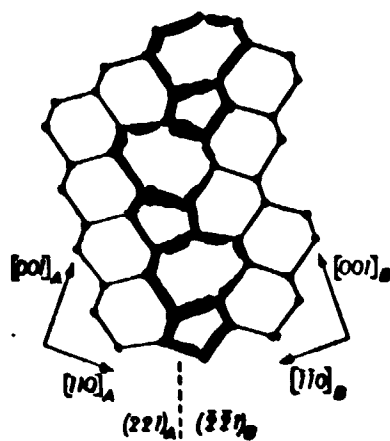
Houstra, J.
1959Physica 25
409-472 $\Sigma = 9$

Fig. 6. Symmetrical tilt boundary with $\theta_1 = 38^\circ 57'$ and zig-zag arrangement of dislocations.

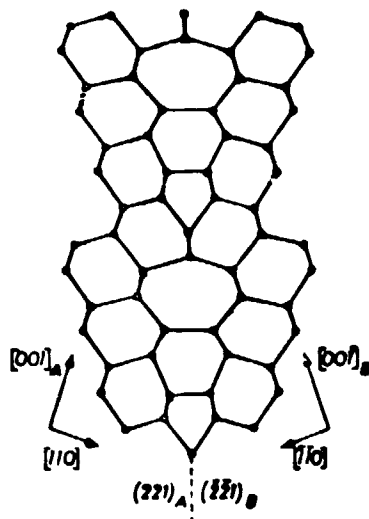
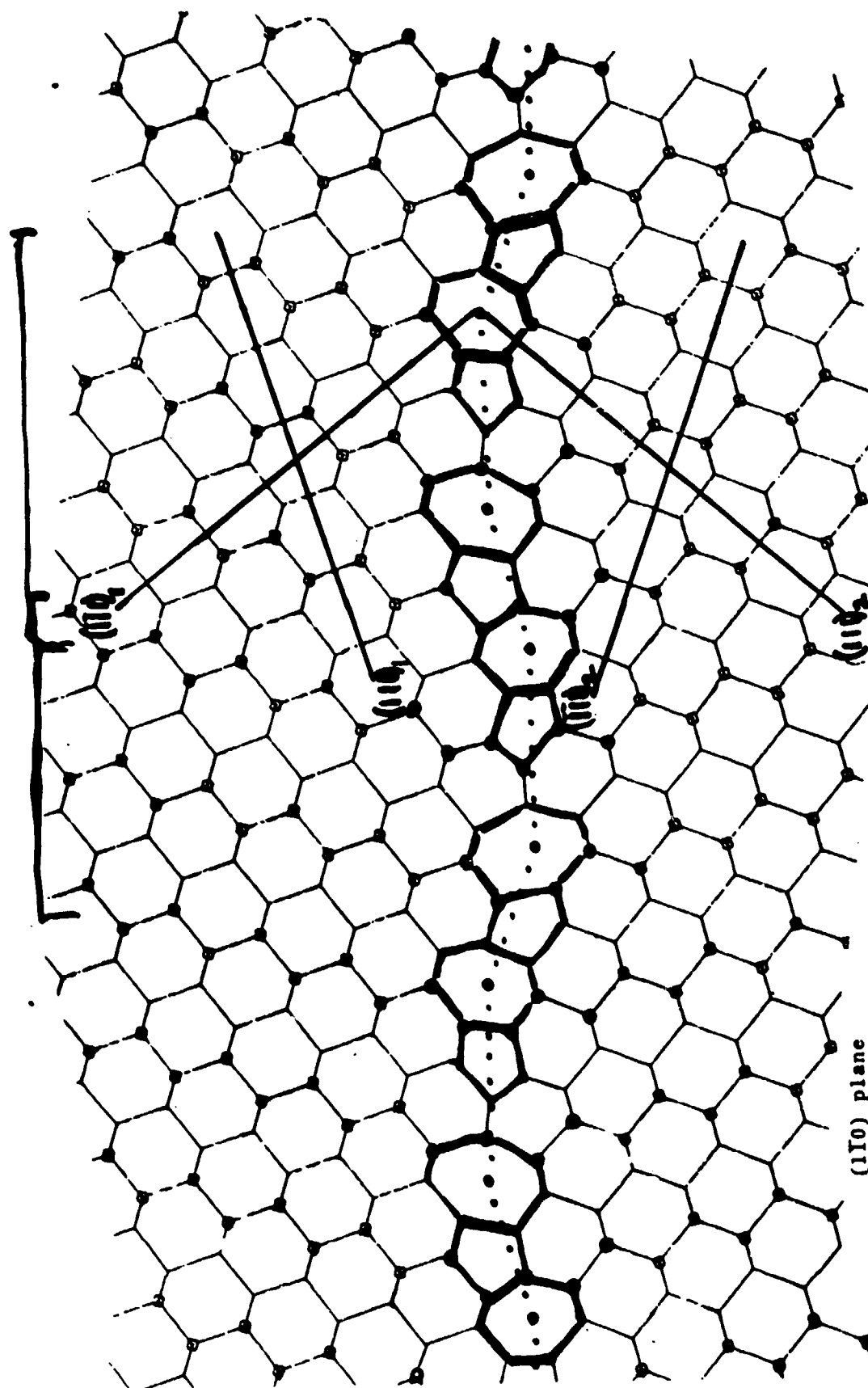
 $\Sigma = 9$

Fig. 7. As Fig. 6 but with overlapping dislocations, thus forming double dislocations.

For ~~the model~~ ($\theta_1 = 31^\circ 35' = \arccos 23/27$) the model ~~is~~
~~the same as in Fig. 6 but with overlapping dislocations, thus forming double dislocations.~~ Thus,

LARGE-AREA SILICON SHEET TASK

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Proposed model for a $\Sigma=5$, $\theta=31.58^\circ$ / $[110]_{1/2}$

GBP = $(SS2)_1$; $(SS2)_2$

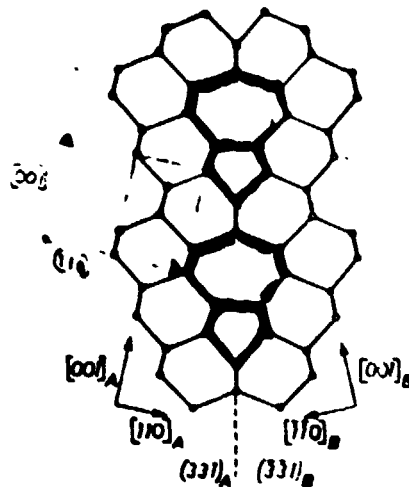
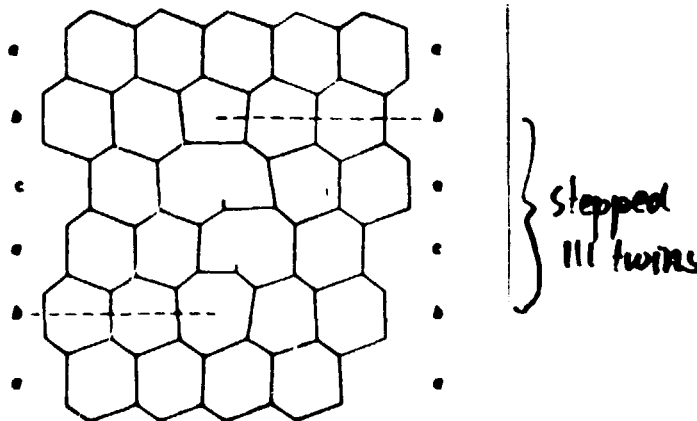
Hornstra, J.
1959Physica 25
409-422• • Atoms at height 0 and $\frac{1}{2}z$

Fig. 5. Projection on $(1\bar{1}0)$ of a symmetrical tilt boundary with tilt axis $[110]$, angle of tilt $\theta_1 = 26^\circ 32'$ and median plane (110) . The height of the atoms above the plane of projection is expressed in $z = \frac{1}{2}a\sqrt{2}$, where a is the lattice constant.

J. Phys. Chem. Solids Pergamon Press 1958, Vol. 5, pp. 129-141.



8. DISLOCATIONS AND TWIN BOUNDARIES

As has been shown in Fig. 13(c), a shift of the twin boundary involves a partial dislocation. A shift of one (double) atomic plane involves a partial of type I, a shift of two planes one of type II, a shift of three planes, however, involves a lattice defect of a different kind. The possible structure of it is shown in Fig. 19(a) for the diamond lattice and in Fig. 19(b) for the f.c.c. lattice. It is no dislocation as its Burgers vector is zero.

Summary

SIGMA = 3

- BOUNDARY PER SE NOT ELECTRICALLY ACTIVE
- ELECTRICAL ACTIVITY CORRELATES WITH PRESENCE OF PARTIAL DISLOCATIONS.
- PARTIAL DISLOCATIONS SHOW ENHANCED ACTIVITY COMPATIBLE WITH JOG MODEL
- EVIDENCE FOR KINK ACTIVITY FROM CURVED PARTIALS.

SIGMA = 9

- 111/115 TWIN SHARES HABIT PLANE WITH FIRST ORDER TWIN - FREQUENTLY MIS-IDENTIFIED AS THE LATTER.
- ELECTRICAL ACTIVITY COMPATIBLE WITH BROKEN BOND MODEL.
- ALTERNATING SECTIONS GIVE DOT-LIKE EBIC CONTRAST SIMILAR TO PARTIAL DISLOCATIONS IN FIRST ORDER TWINS.

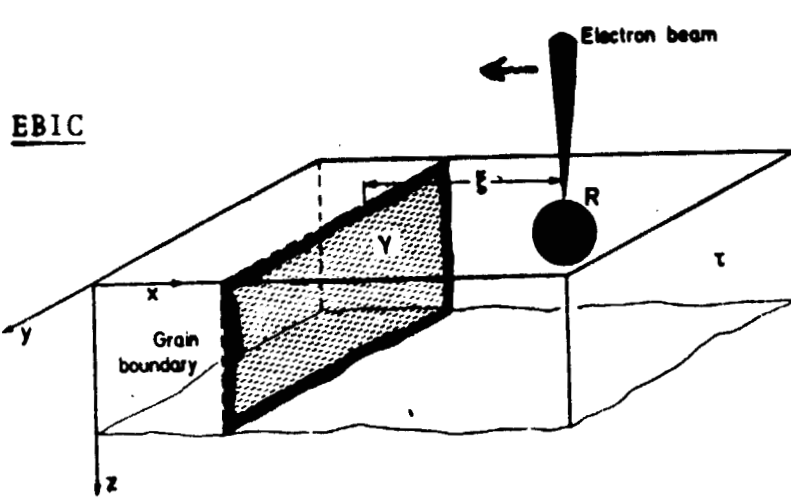
SIGMA = 27

- CHARACTER OF BOUNDARY DEPENDS ON BOUNDARY PLANE VARIES OVER SHORT DISTANCES (0.1 μm).
- UNSYMMETRIC GBP CORRELATED TO DISSOCIATED BOUNDARIES:
 $\text{SIGMA}_{27} = \text{SIGMA}_9 + \text{SIGMA}_3$
- MICROFACETTING IN ACCORDANCE WITH HORNSTRA.
- UNDISSOCIATED BOUNDARY ON SYMMETRIC GBP HAS STRUCTURE OF 5 and 7 MEMBERED RINGS SHOULD LEAD TO GAP STATES.

Summary of Sigma = 27

- o Undissociated 255/255 is symmetric.
and located on second highest density
CSL (highest 115/115)
- o Dissociated section is un-symmetric.
Components :Symmetric SIGMA 9 112/112
(2 nd highest after 111/115)
- o Largest facet is SIGMA 3 111/111 coherent
twin
- o Other facet: probably 111/115
- o 3 Step periodicity correlated to stacking
sequence - Hornstra model of atomistic faceting.
(Brockman).

Techniques



EBIC contrast of grain boundaries can be calculated by solving the 3-D diffusion equation under the following assumptions (J.Marek)

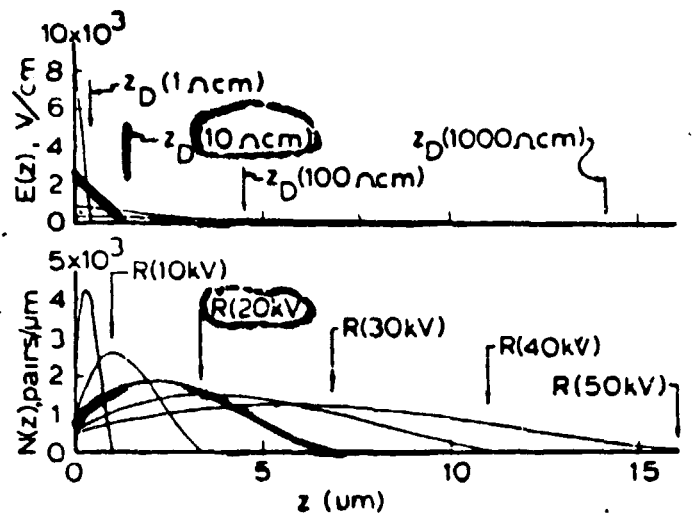
- o ∞ recombination velocity at the boundary plane
- o $R_p \gg$ depletion layer thickness.

Typical operation conditions for 10 cm Si

$$d \approx 1\mu\text{m}$$

$$R_p \approx 6\mu\text{m} \text{ (30 Kev)}$$

Maximum contrast when $R_p \approx L$.



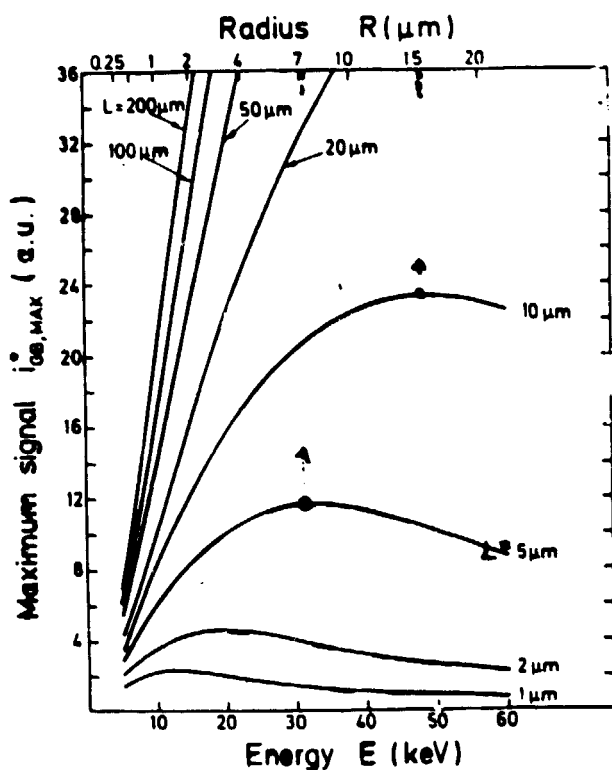
After Leamy et al.

$$R = \alpha E^{1.75}$$

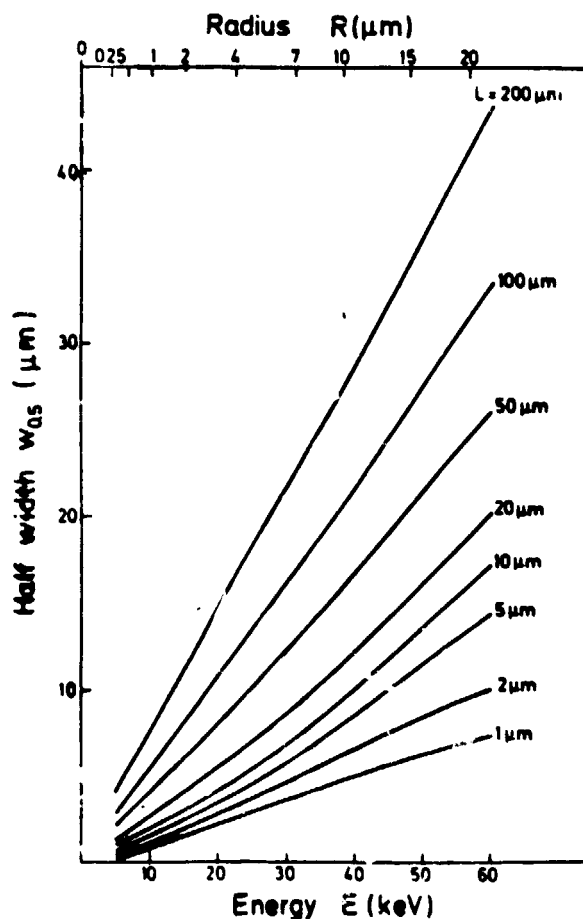
Recent results indicate α may be twice as high as indicated above.

LARGE-AREA SILICON SHEET TASK

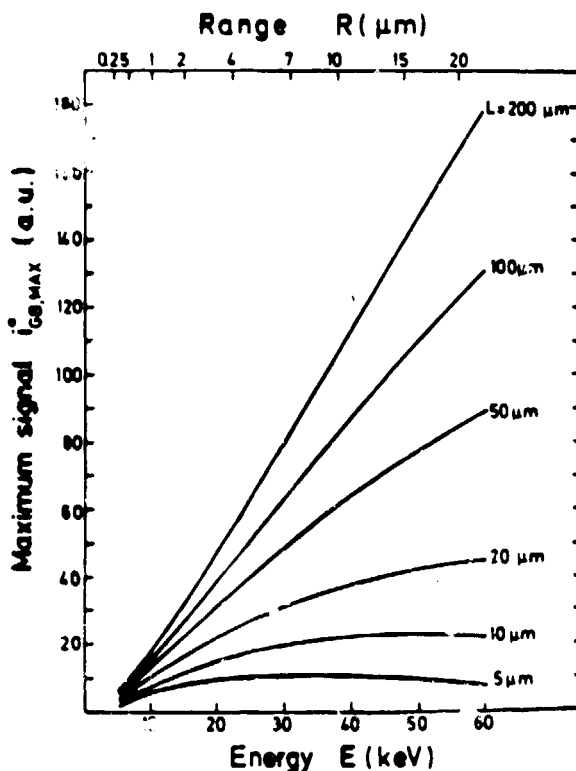
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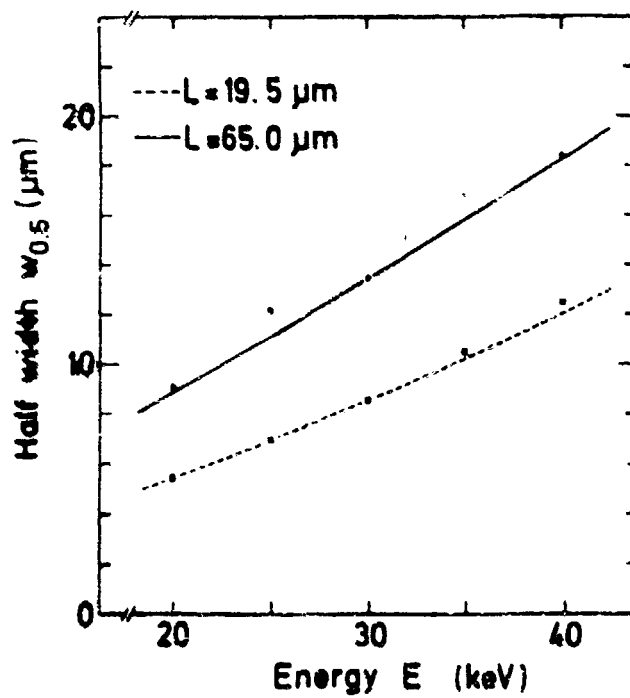
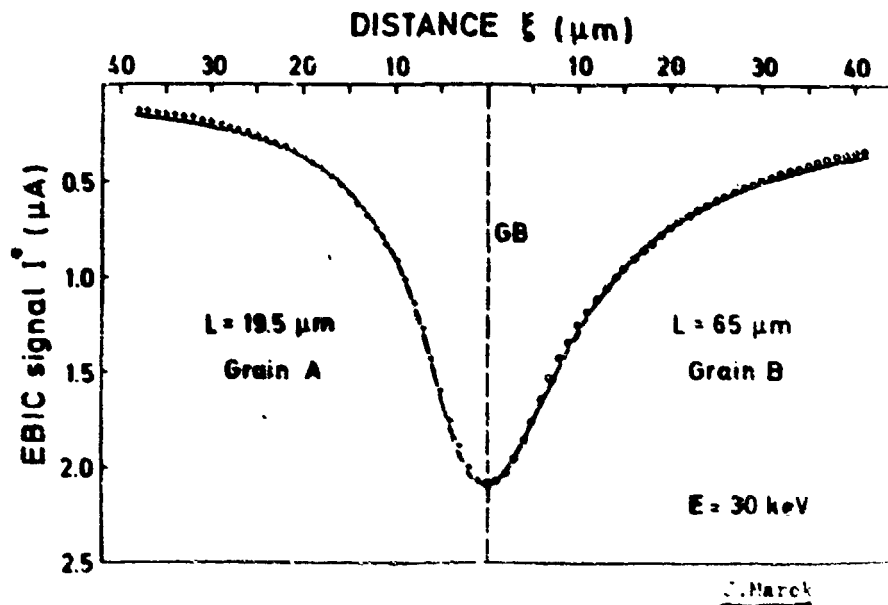
J. Marek



J. Marek



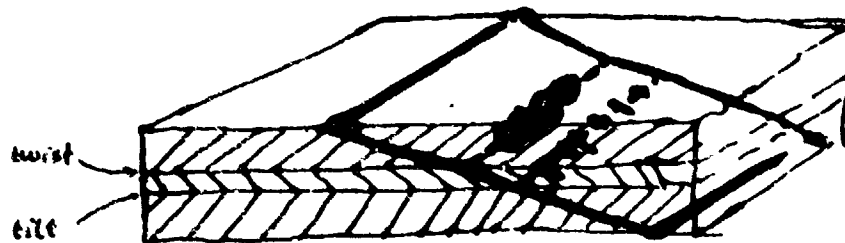
J. Marek



J. Marek

Web

- 0 Contains one or several twin planes
in center plane of ribbon



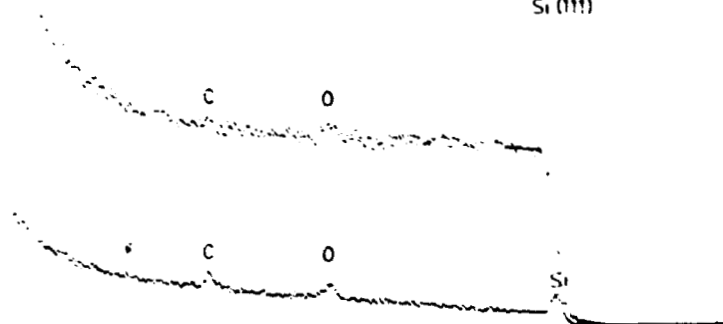
- 0 Shallow bevel allows EBIC imaging of
dislocation network on these twins
- 0 Rotational misfit of seconds of arc
results in sufficiently large spacing
to be resolved by EBIC.

LARGE-AREA SILICON SHEET TASK

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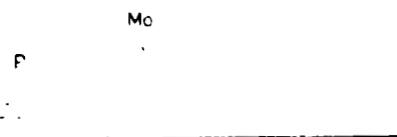
20784 5062
50 0 LT= 656 CT= 662 4096FS 562 0

Rutherford Backscattering
2 MeV 15 μ C
Processed Web Cell
Si (111)



19412 5062
50 0 LT= 5956 CT= 5960 LOG 562 0

Rutherford Backscattering
1 MeV 50 μ C
Processed Web Cell
Si (111)



Problems and Concerns

- Statistics of Results .

Time and manpower restrictions confine analysis to a few specimen of a given material. Thus, some caution must be exercised when applying results to the population as a whole, especially for materials in which the crystal growth and processing techniques are continuously refined.

GRAIN BOUNDARY INVESTIGATION

JET PROPULSION LABORATORY

L.J. Cheng

Participants

LI-JEN CHENG

GERRY CROTTY

TAHER DAUD

KATHY DUMAS

SANDY HYLAND

TOM MacCONNELL

RINDGE SHIMA

CHIN-MIIN SHYU

KATE STIKA

Objective

TO DEVELOP BETTER POLYCRYSTALLINE SILICON SOLAR CELLS
THROUGH BETTER UNDERSTANDING OF THE BEHAVIOR OF GRAIN
BOUNDARIES IN SILICON

Approach

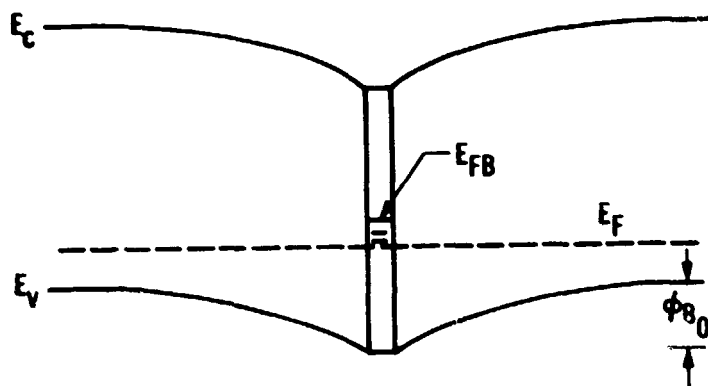
EXPERIMENTAL STUDIES ON SAMPLES OF

- LARGE GRAIN SILICON INGOTS
(WACKER, SEMIX, AND HEM)
- CZ BICRYSTALS WITH CONTROLLED
LATTICE MISMATCH

Subjects Under Study

- BICRYSTAL GROWTH
- ELECTRONIC TRANSPORT PHENOMENA
 - POTENTIAL BARRIER
 - CARRIER RECOMBINATION
 - TRAPPING STATES
- ATOMIC TRANSPORT PHENOMENA
 - ENHANCED DIFFUSION OF IMPURITIES
 - IMPURITY GETTERING
- EFFECTS ON SOLAR CELL PERFORMANCE

Energy-Band Diagram at Boundary Region for p-Type Si



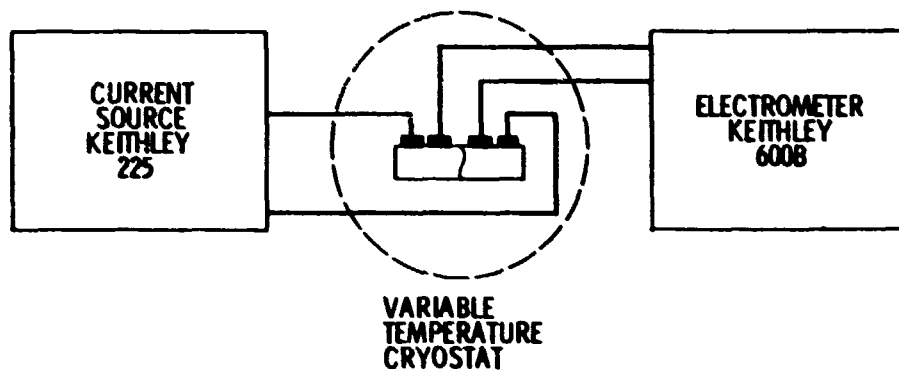
$$\phi_{B0} = E_A + T \frac{\partial \phi_{B0}}{\partial T}$$

$$\phi_{B0} = \frac{qQ^2}{8\epsilon_0 \epsilon N_A}$$

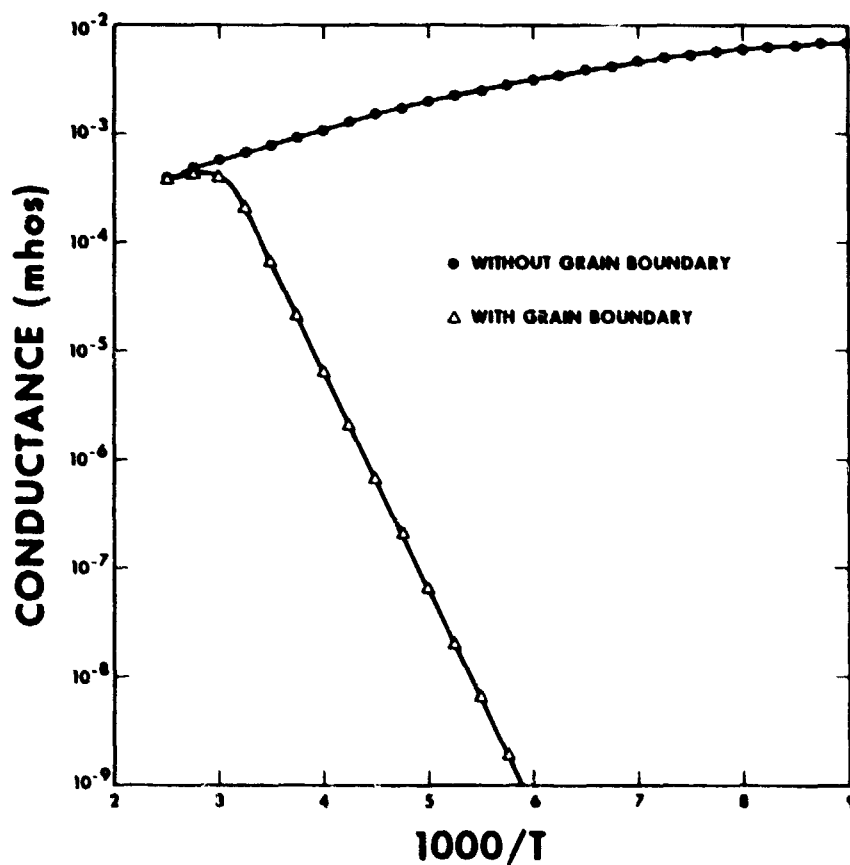
$$Q = \frac{\epsilon_0 \epsilon N_A}{C_0}$$

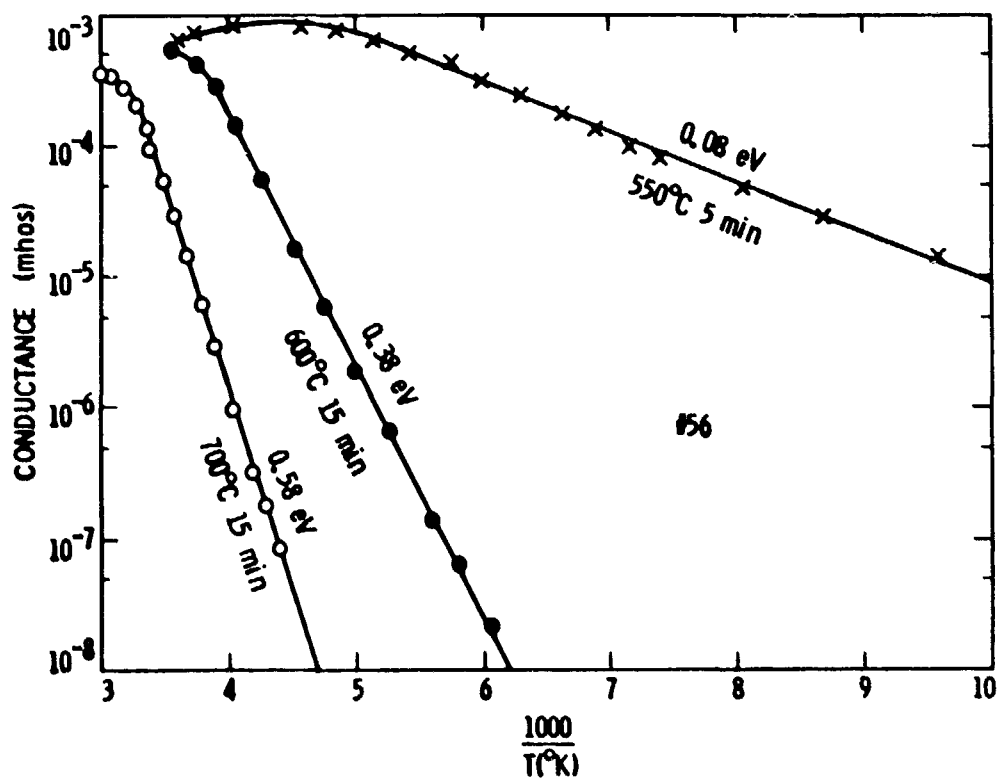
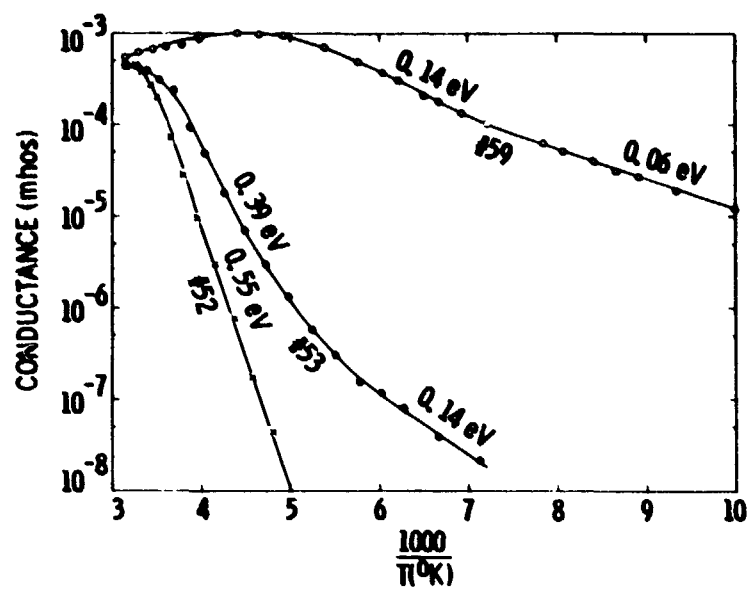
$$Q = \int_{E_{FB}}^{E_F} dE, \sigma dE$$

Experimental Arrangement for Zero-Bias Conductance Measurements



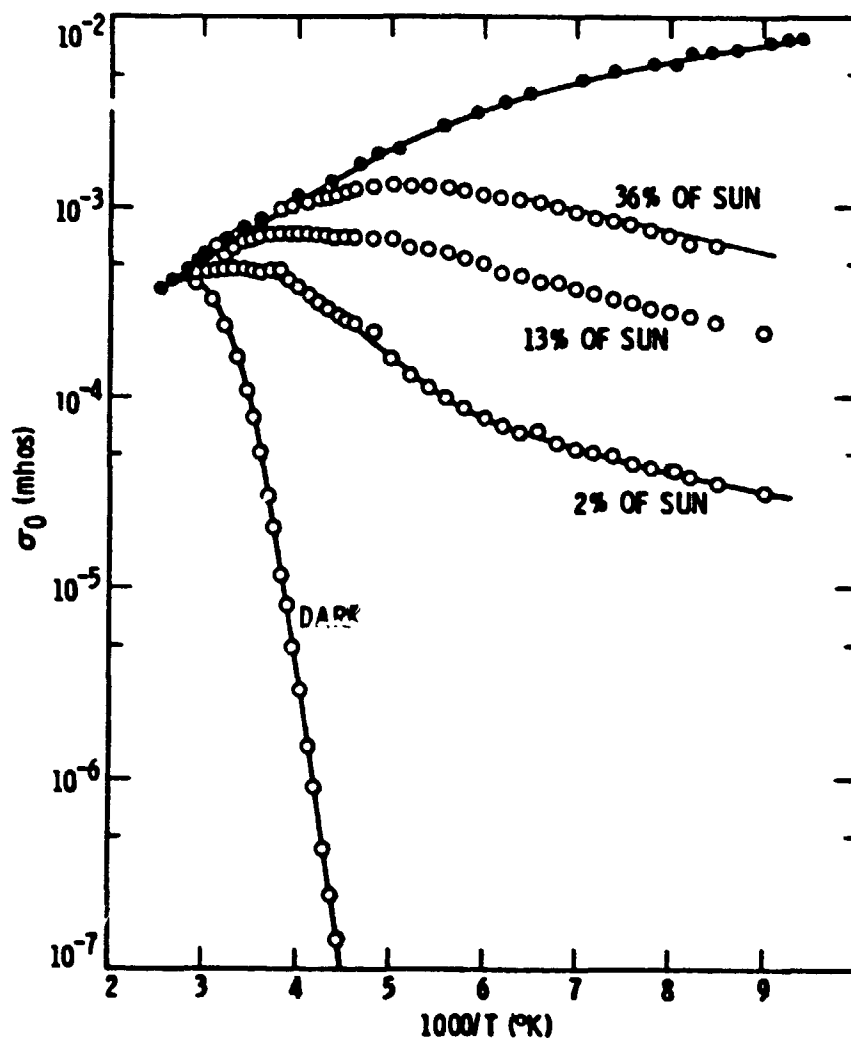
Temperature Dependence





LARGE-AREA SILICON SHEET TASK

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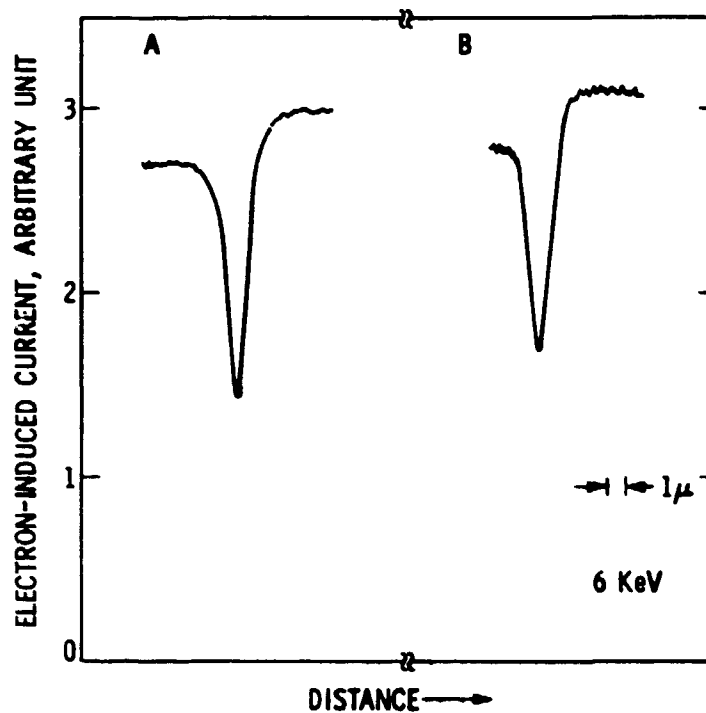
Potential Barrier

RESULTS:

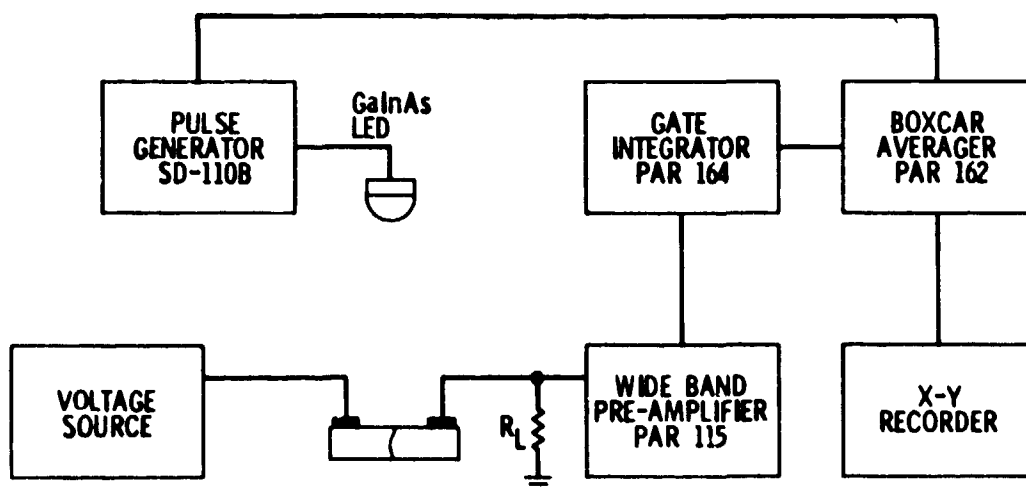
- CONSIDERABLE VARIATION IN E_A ALONG GRAIN BOUNDARIES, PRESUMABLY DUE TO VARIATION OF LOCAL DISORDERS
- INCREASE OF E_A WITH ANNEALING TEMPERATURE, LIKELY DUE TO LOCAL DEFECT CHANGES AND IMPURITY GETTERING
- DECREASE OF ϕ_B WITH LIGHT INTENSITY, CAUSED BY MINORITY CARRIER TRAPPING

LARGE-AREA SILICON SHEET TASK

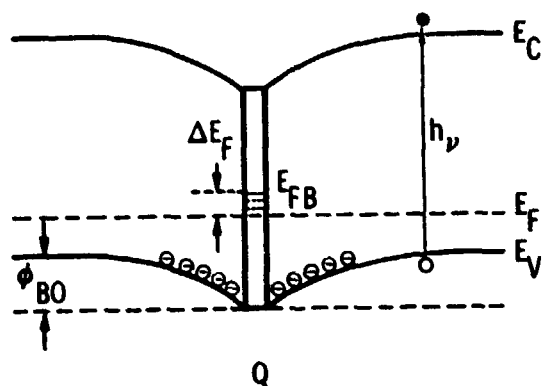
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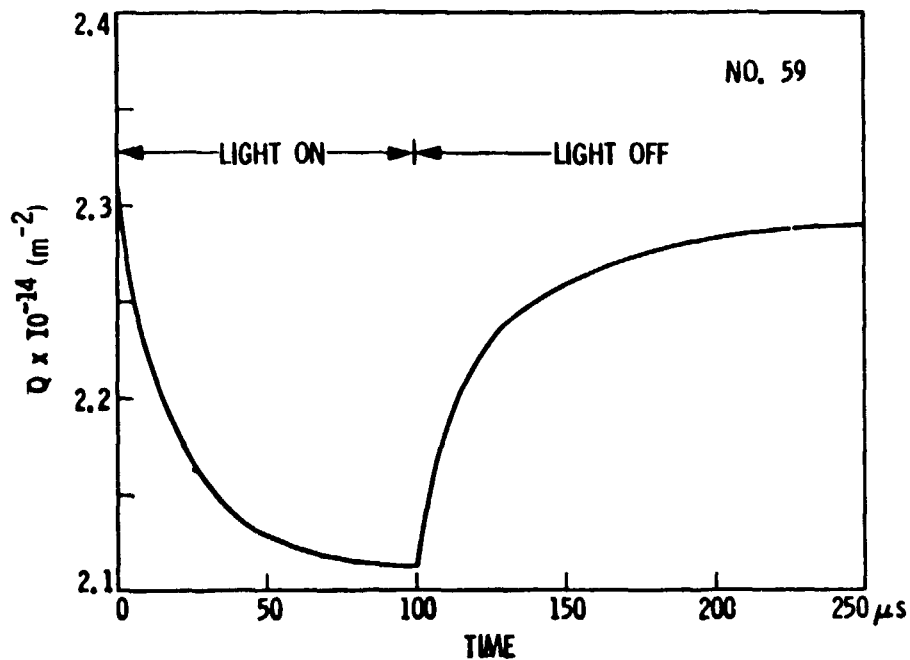
Experimental Arrangement for Photoconductivity Measurements



Light Effects on Grain Boundary Properties



- DECREASE OF Q
- INCREASE OF G_0
- CREATION OF CARRIER RECOMBINATION CURRENT



LARGE-AREA SILICON SHEET TASK

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UNDER ILLUMINATION,

$$\frac{dQ}{dt} = J_{maj} - J_{min}$$

$$(J_{maj} = J_{min} \text{ AT THE EQUILIBRIUM})$$

AND, IN THE DARK AFTER THE LIGHT IS OFF,

$$\frac{dQ}{dt} = J_{maj},$$

WHERE

$$J_{maj} = (2cA - B) \exp(-(E_F + \phi_{BO})/kT)$$

$$J_{min} = \frac{D_e}{e L_e} (n_{\infty} - n_0)$$

RECOMBINATION VELOCITY AT THE GRAIN BOUNDARY

$$S = \frac{J_{min}}{e n_0}$$

Electrical Properties of Grain Boundaries

Sample No.	E_g (eV)	G_0 (mho/m ²)	ϕ_{BO} (eV)	Q (/m ²)	I^*	S (m/s)
51	0.55	5.98×10^2	0.12	5.66×10^{14}	0.66I	2.5
					I	6.4
59	0.10	2.45×10^3	0.02	2.22×10^{14}	I	0.88
					1.8I	1.09

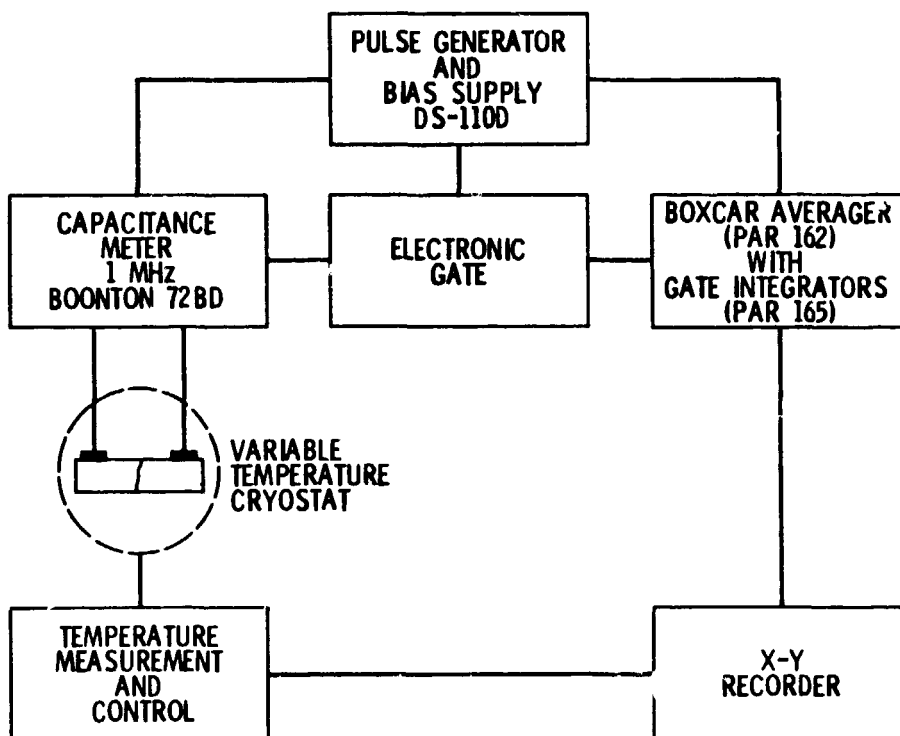
*I = Light intensity which creates an equilibrium minority carrier density of 1.08×10^{16} electrons/m³ in the bulk of the sample.

Recombination Velocity

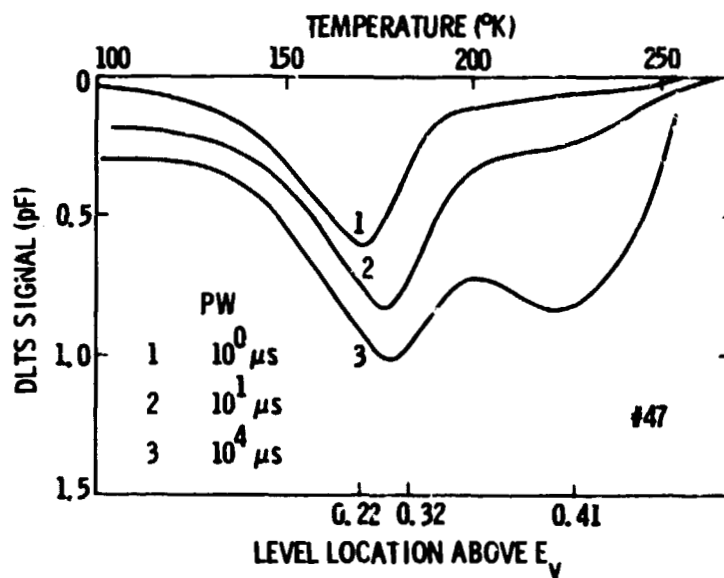
RESULTS:

- DEVELOPED A TECHNIQUE USING PHOTOCONDUCTIVITY IN CONJUNCTION WITH ϕ_{BO} (D) AND Q(D) MEASUREMENTS FOR THE MEASUREMENT OF MINORITY CARRIER RECOMBINATION VELOCITY AT THE GRAIN BOUNDARY
- OBSERVED INCREASES OF S WITH BOUNDARY STATE DENSITY AND LIGHT INTENSITY

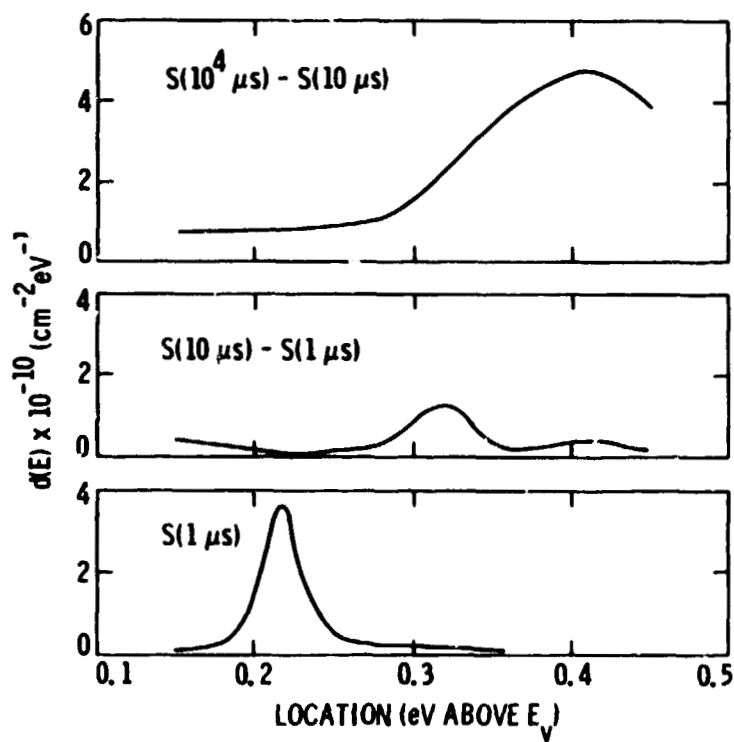
Experimental Arrangement for DLTS Measurements



Pulse Width Dependence



Distribution of the Density of States

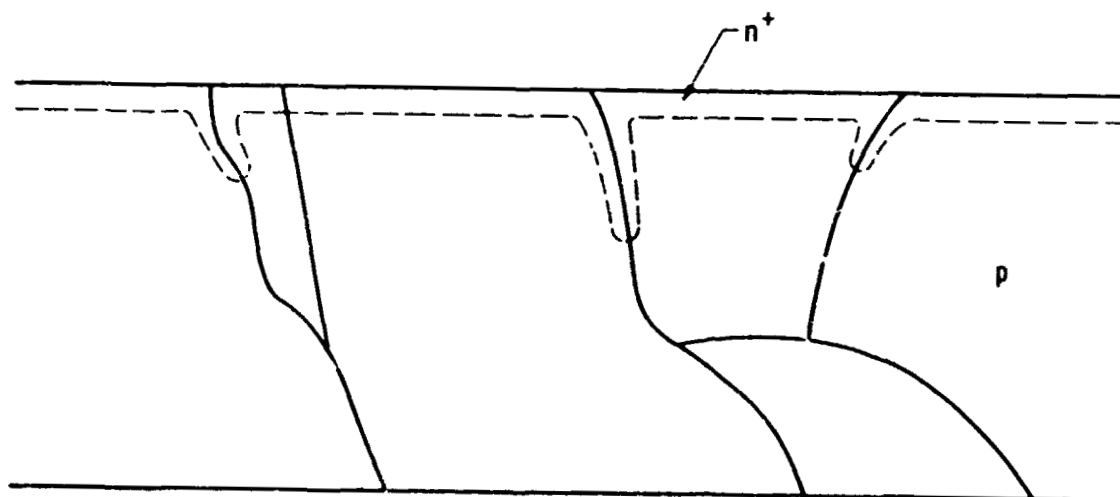


Electronic States

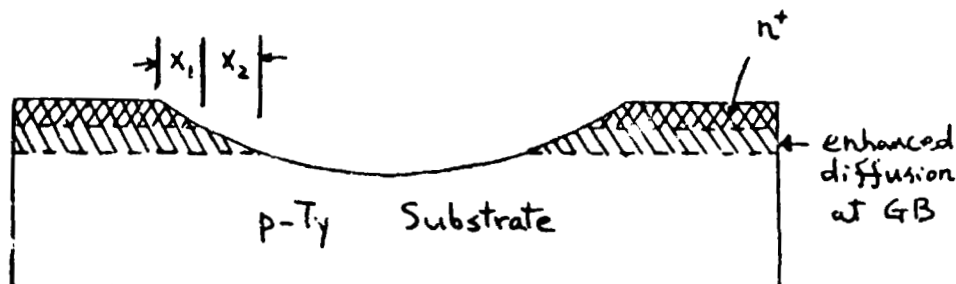
RESULTS:

- DEMONSTRATED THE APPLICATION OF DEEP LEVEL TRANSIENT SPECTROSCOPY (DLTS) IN THE STUDY OF ELECTRONIC STATES AT GRAIN BOUNDARIES OF SILICON
- OBSERVED A TREND THAT THE DENSITY OF GRAIN BOUNDARY STATES IS GENERALLY INCREASING WITH THE DISTANCE FROM THE EDGES OF THE BAND GAP. HOWEVER, THE DETAILS VARY CONSIDERABLY FROM SAMPLE TO SAMPLE WHICH CAN BE ATTRIBUTED TO LOCAL VARIATION OF DISORDERS

Cross Section of Phosphorus-Diffused Polycrystalline Silicon



Cross Section of Grooved Sample at Grain Boundary



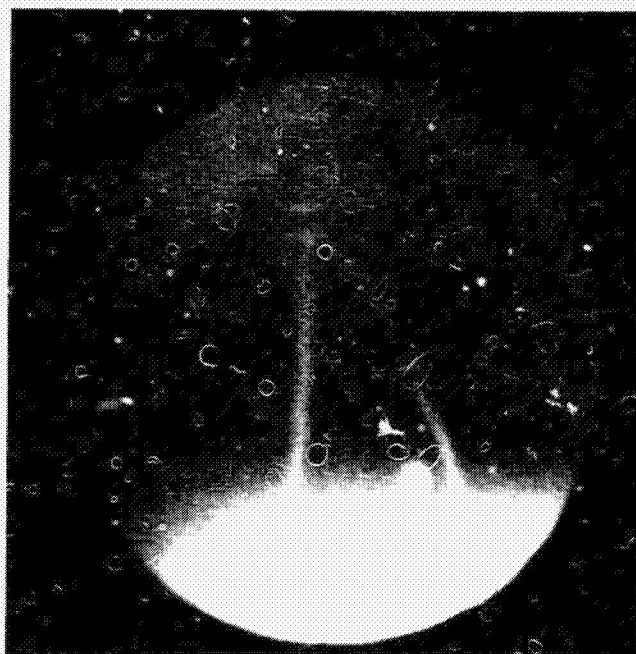
Staining !

F with light

Enhanced Diffusion of Phosphorus



GROOVED AND STAINED

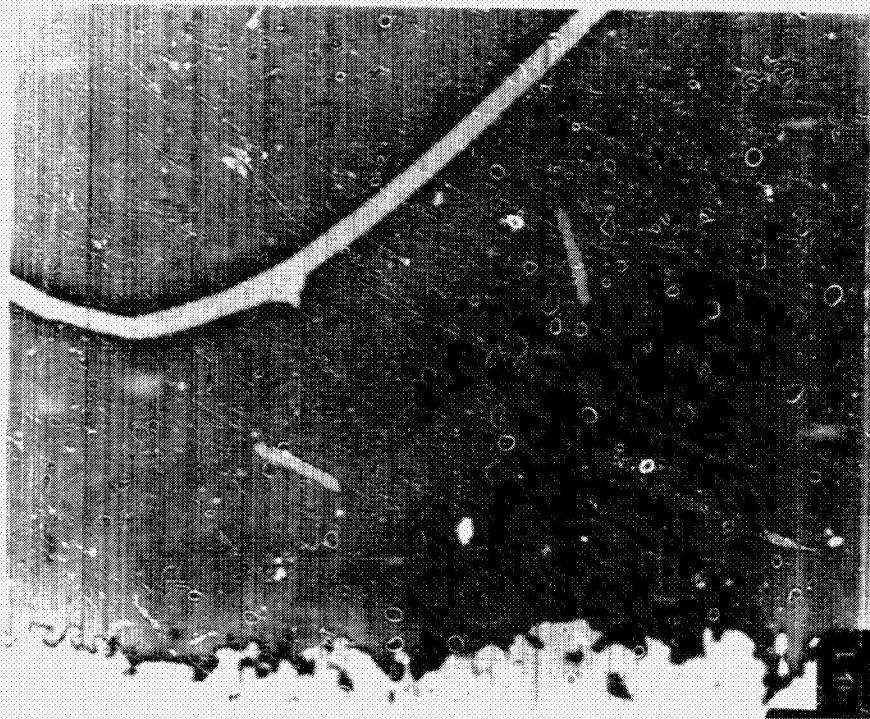


SiP⁻ ION IMAGE

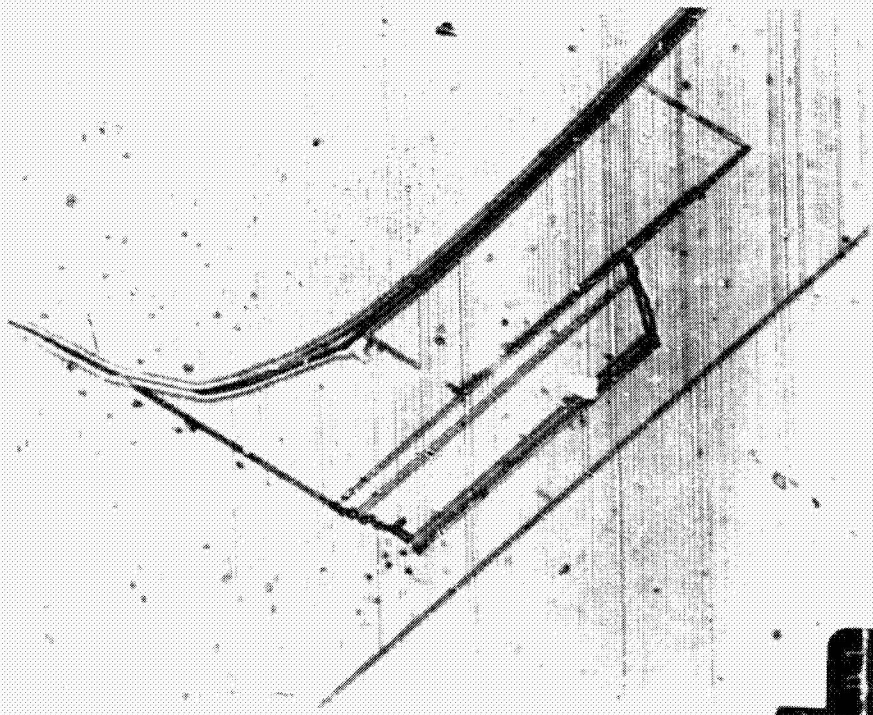
LARGE-AREA SILICON SHEET TASK

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Grooved and Stained



Sirtl-Etched



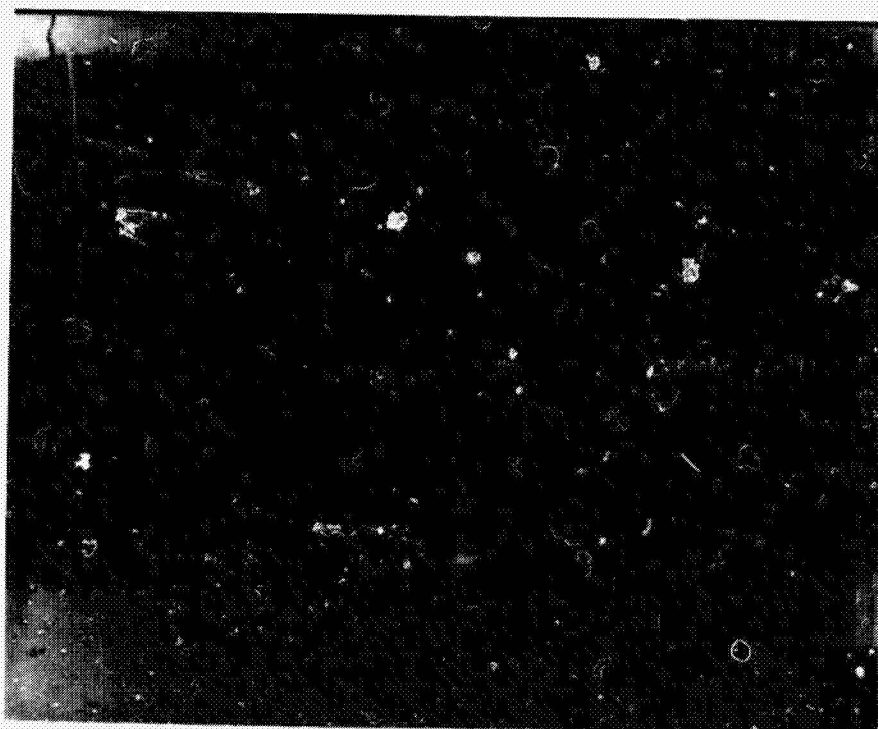
LARGE-AREA SILICON SHEET TASK

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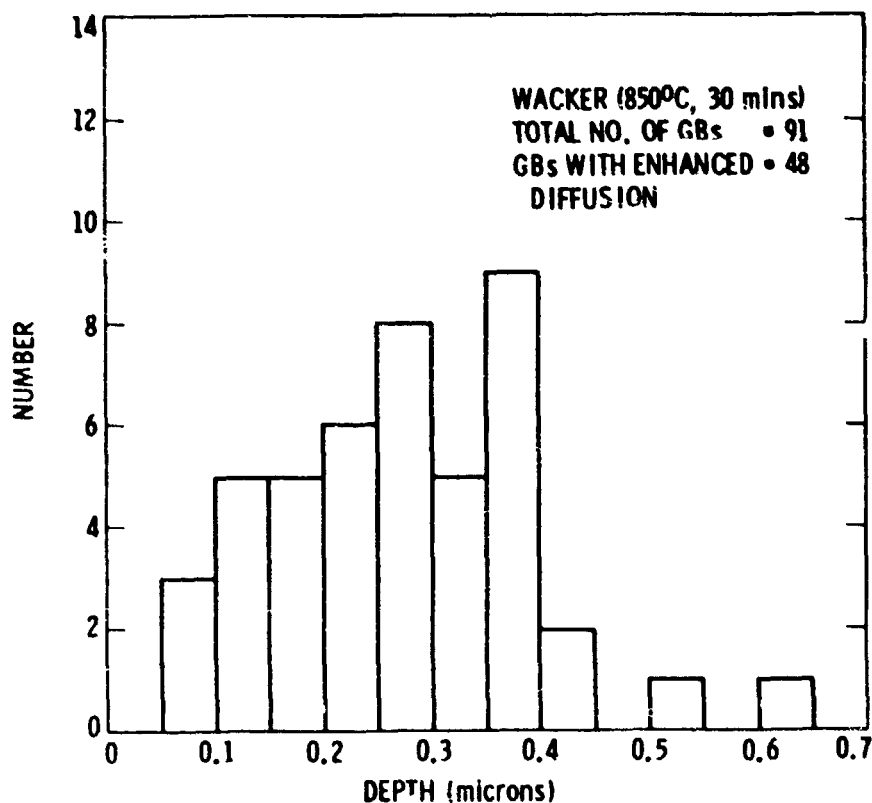
EBIC



Grooved and Stained



Depth of Diffused Regions at Grain Boundaries



Enhanced Diffusion of Phosphorus

RESULTS:

- THE GROOVING AND STAINING TECHNIQUE IS A SUITABLE METHOD FOR THE OBSERVATION OF ENHANCED DIFFUSION OF PHOSPHOROUS AT GRAIN BOUNDARIES IN SILICON
- THE ENHANCED DIFFUSION OCCURS ONLY AT "HIGH-ORDER" GRAIN BOUNDARIES, GENERALLY ASSOCIATED WITH HIGH CARRIER RECOMBINATION
- THE DEPTH OF THE ENHANCED DIFFUSION VARIES DRASTICALLY FROM BOUNDARY TO BOUNDARY, WHICH MAKES THE QUANTITATIVE MEASUREMENT DIFFICULT UNLESS THE GRAIN BOUNDARY IS WELL CHARACTERIZED

LARGE-AREA SILICON SHEET TASK

Present Activities and Plans

- **DENSITY OF STATES, RECOMBINATION VELOCITY, AND BARRIER HEIGHT
AS FUNCTIONS OF LATTICE MISMATCH AND PROCESS PARAMETERS
(INCLUDING PASSIVATION)**
- **QUANTITATIVE STUDIES ON ENHANCED DIFFUSION OF PHOSPHOROUS**
- **IMPURITY BEHAVIOR (e.g., CARBON, AND OXYGEN)**
- **EFFECTS ON SOLAR CELL PERFORMANCE**

STUDY OF ABRASIVE-WEAR RATE OF SILICON

UNIVERSITY OF ILLINOIS AT CHICAGO

J. Clark
D.S. Lim
S. Danyluk

TECHNOLOGY Materials Properties Modification	REPORT DATE April 22, 1982
APPROACH An experimental program is carried out to study the fundamental mechanisms of abrasion and wear, and deformation of silicon by a single crystal diamond in various fluid environments. CONTRACTOR University of Illinois at Chicago	STATUS The abrasion rate and depth of damage of (100) and (111) p-type silicon in three fluid environments has been determined. The surface deformation mechanism was found to change when the fluid was varied. The diamond geometry affects the wear rate. There appears to be a correlation between the wear rate and the dielectric constant of the fluid. The brittle lateral crack model does not appear to describe the wear rates measured.
GOALS Develop a model for surface-mechanical property modification of silicon under the influences of fluid environments	

Introduction

Optical and scanning electron microscopy are used to determine the wear rate and deformation mechanism of diamond abrading (100) and (111) Cz silicon in water, ethanol and acetone. A multi-scratch experiment is used to determine the effects of normal force on the abrading diamond and fluid on the abrasion rate and depth of damage. These results are compared with a lateral crack model of abrasion of brittle materials.

LARGE-AREA SILICON SHEET TASK

Variables

Fluid, Temperature, Voltage, Photo-Irradiation, Normal Force (F_N), Orientation, Abrasion Speed.

Data

Groove depth vs. variables, SEM of groove surface, depth of damage.

Analysis

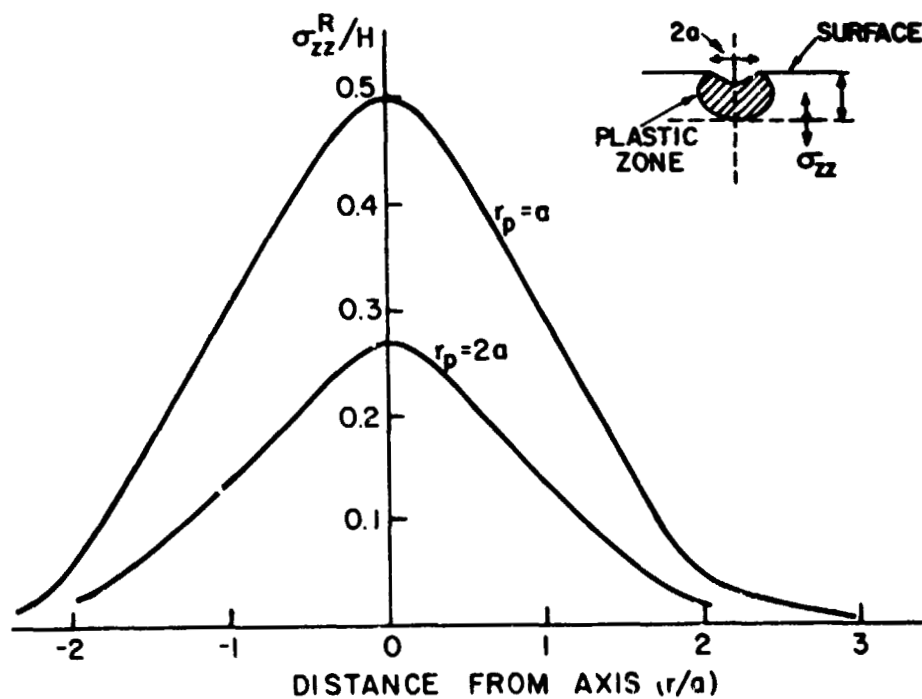
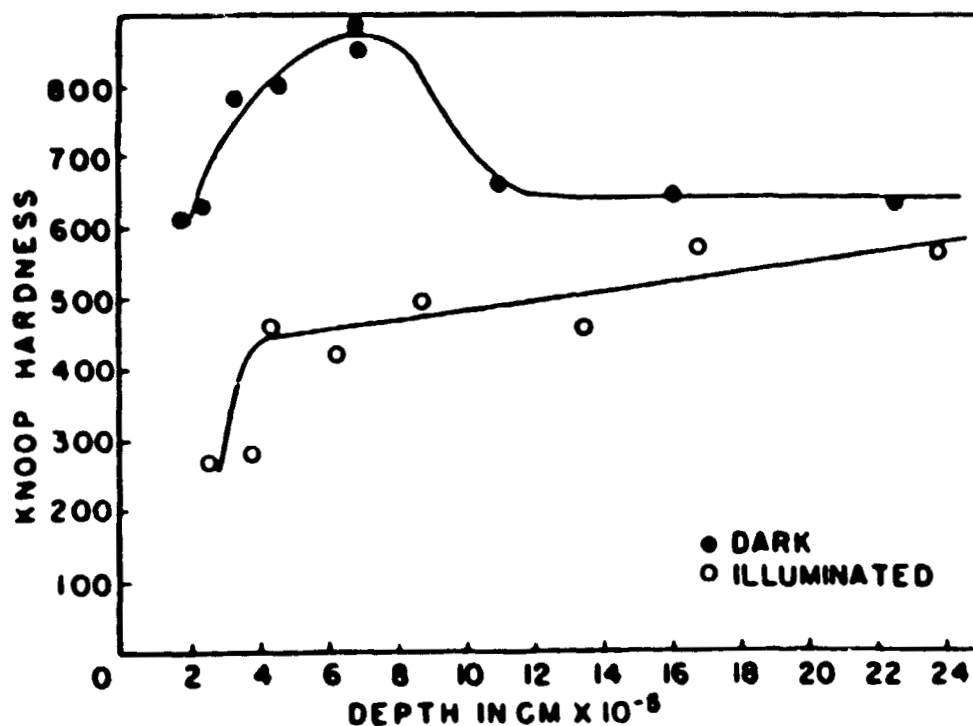
Stress analysis, depth of damage, lateral crack model.

Summary of Results

1. Wear rate varies by ~100% (acetone; ethanol; water).
2. Depth of damage larger for water than ethanol.
3. (100) and (111) wear rates are different.
4. Dielectric constant of the fluid related to the silicon hardness.
5. Lateral crack model describes wear rate when $F_N \gtrsim 60$ g.

Changes in Surface Hardness of Silicon

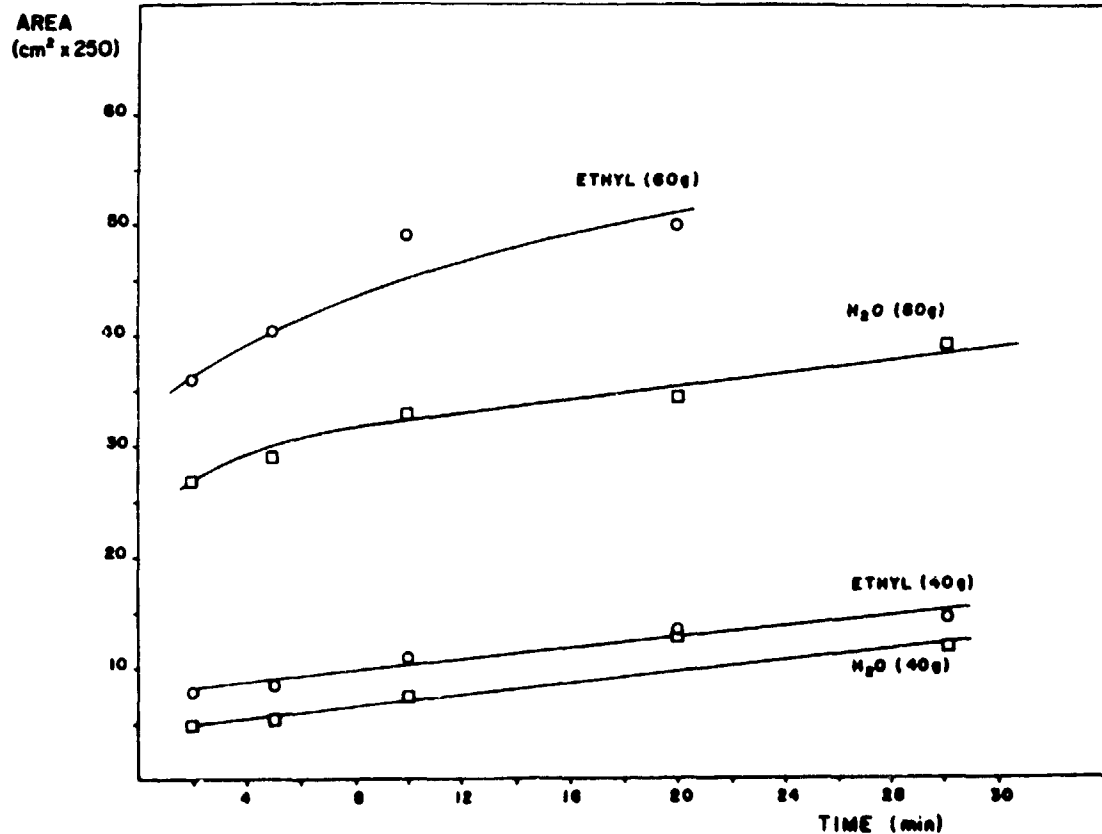
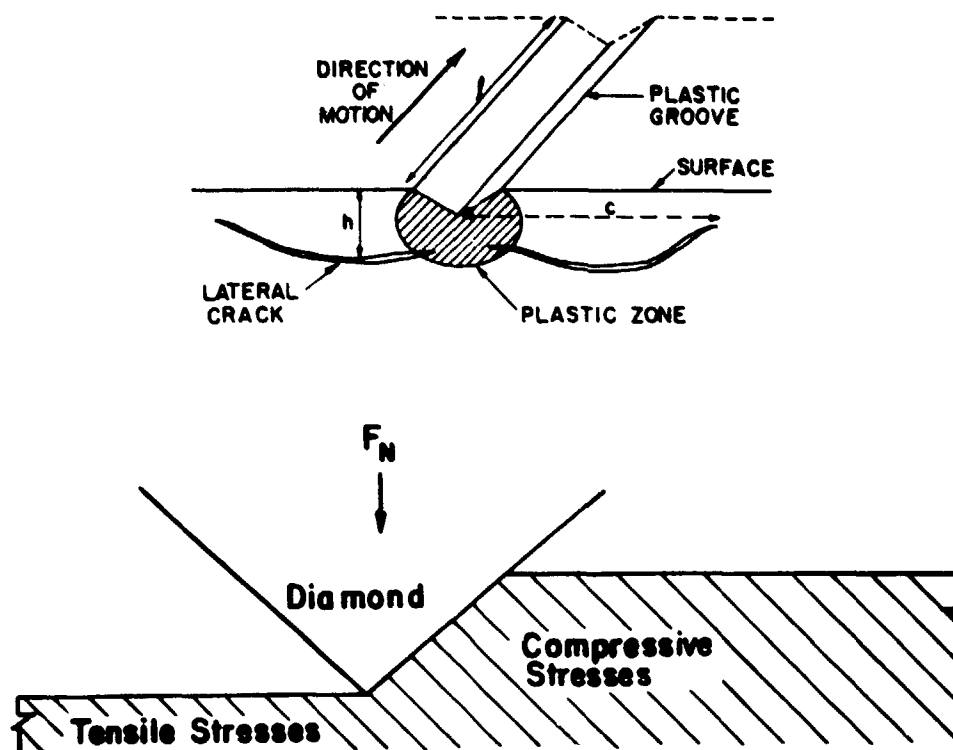
<u>Reference</u>	<u>Effect</u>	<u>Percent Softening</u>	<u>Comments</u>
Kuczynski and Hochman	Photon irradiation	70% softening	Intensity and surface preparation important; microhardness test
Ablova	H ₂ O adsorption	Softening	Surface preparation and impurity content important; microhard- ness test
Westbrook and Gilman	Potential between indenter and crystal	60% softening	Disappeared at elevated temperatures; micro- hardness test
Yost and Williams	NaCl and Na ₄ P ₂ O ₇	50-80% softening depending on concentration	Zeta-potential measurements of crushed silicon
Cuthrell	CCl ₄ and H ₂ O adsorption	Not determined	Adsorption changed mode of drilling
This work	H ₂ O, ethanol, acetone adsorption	Up to 70% soften- ing dependent on type of fluid and F _N	Pyramid diamond scratch test



The spatial dependence of the residual tensile stress along a plane through the intersection of the plastic zone with the penetration axis: the stresses were estimated from an analytic elastic/plastic solution for a spherical cavity and an elastic solution for a half space.

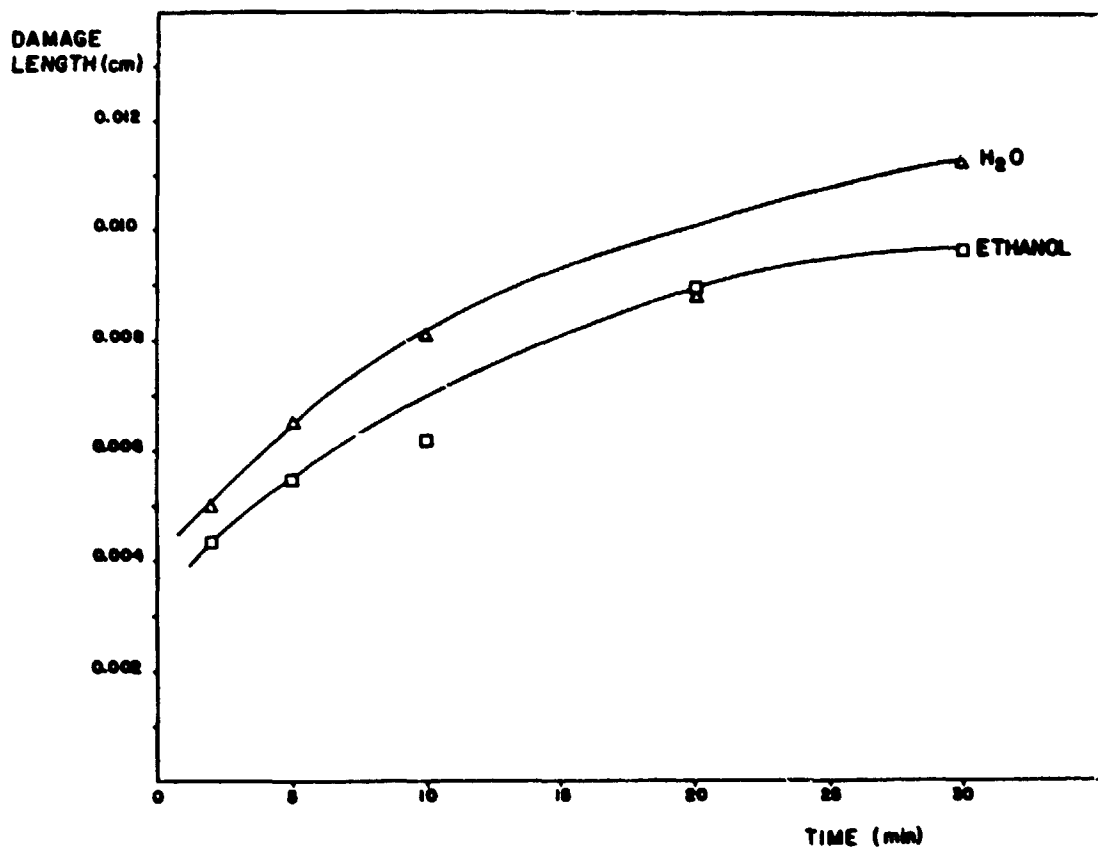
LARGE-AREA SILICON SHEET TASK

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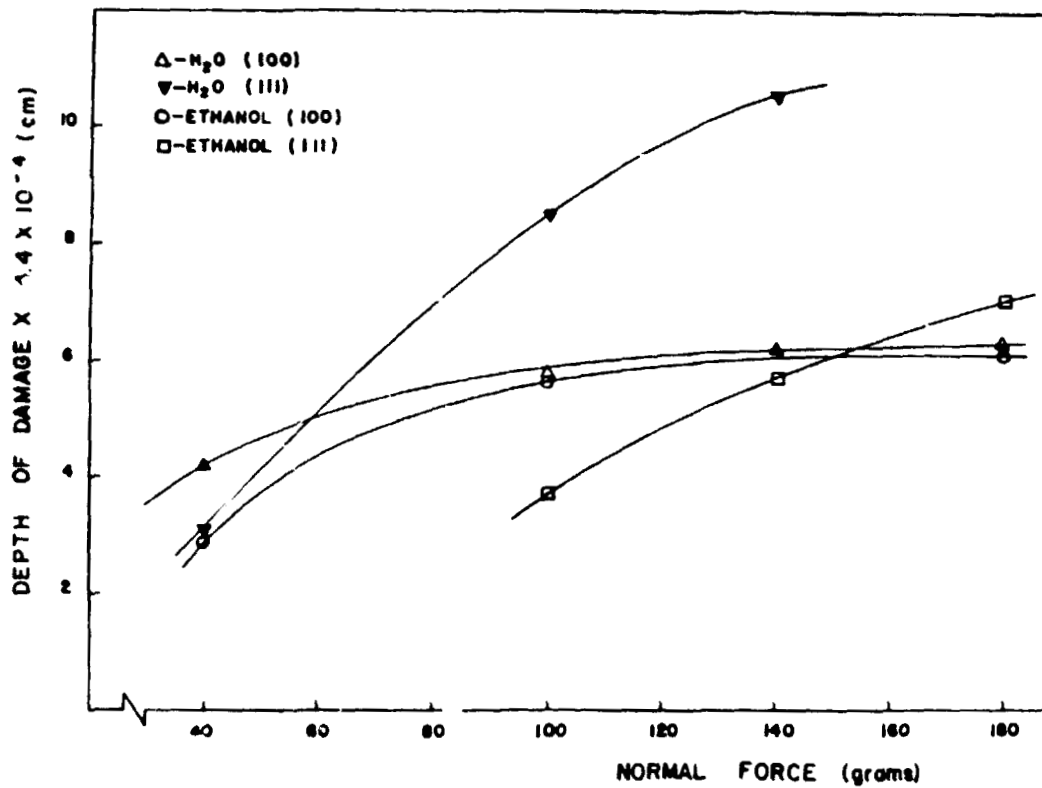
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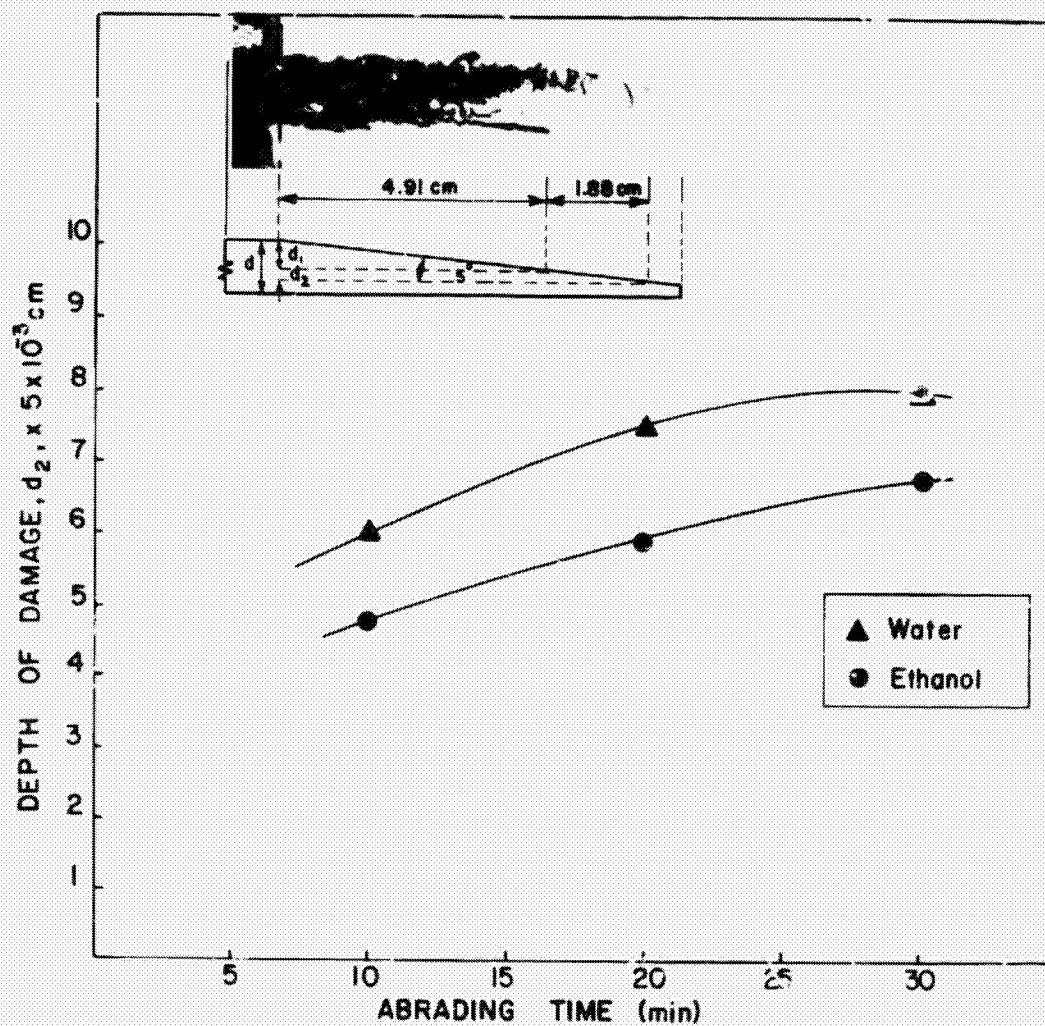


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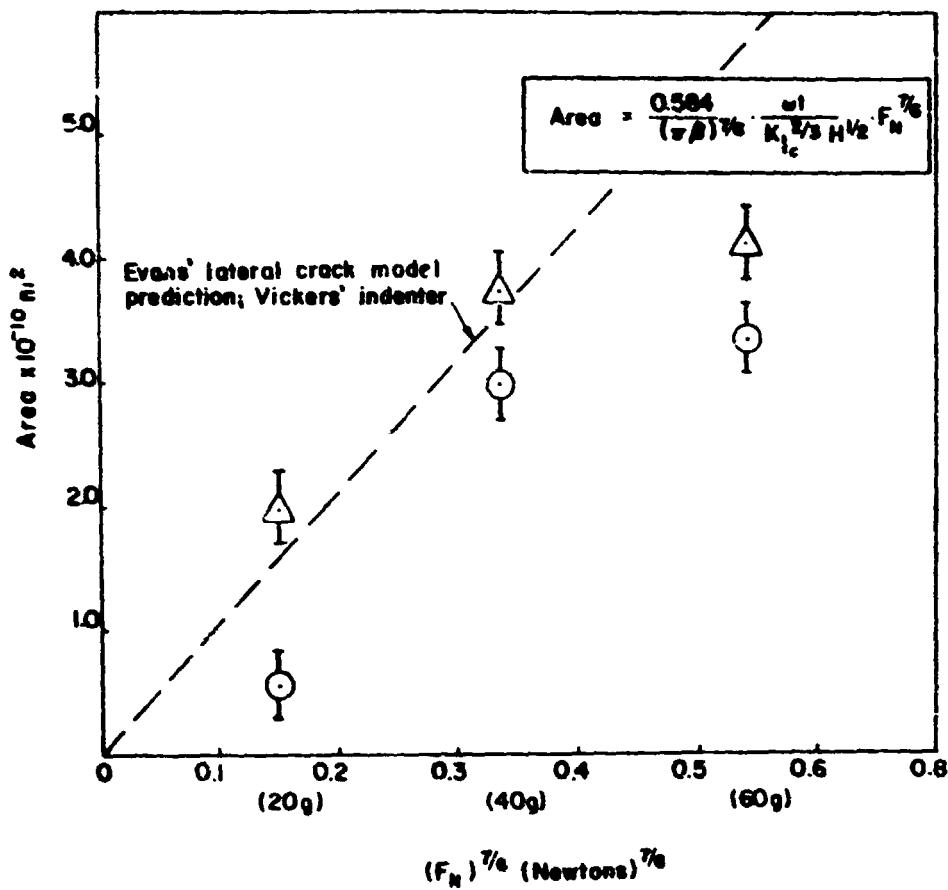
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Depth of Damage From Single Scratch Abrasion on Silicon





Depth of Damage in (100) p-Type Silicon Formed by a Diamond at Room Temperature vs Abrasion Time (min.). The Fluid Environment Was Varied. The Normal Force Was $F_N = 40 \text{ g}$.



Problems and Concerns

The diamond geometry changes during the abrasion experiments due to microcracking at the diamond surface.

The diamond vibration must be stabilized.

The temperature at point of contact between the diamond and the silicon is unknown.

SOLAR CELL FABRICATION AND ANALYSIS

APPLIED SOLAR ENERGY CORP.

TECHNOLOGY SOLAR CELL FABRICATION & ANALYSIS	REPORT DATE APRIL 22, 1962
APPROACH 1) FABRICATION OF SOLAR CELLS BY BASELINE & ADVANCED PROCESSES POSSIBLY INCLUDING GETTERING AND ANNEALING. 2) ANALYSIS USING DARK AND LIGHT I-V, DIFFUSION LENGTH MEASUREMENTS, SPECTRAL RESPONSE. CONTRACTOR APPLIED SOLAR ENERGY CORPORATION	STATUS
GOALS 1) AN UNDERSTANDING OF THE MECHANISMS THAT LIMIT THE DEFICIENCIES OF SOLAR CELLS MADE FROM VARIOUS SILICON SHEETS. 2) AN UNDERSTANDING OF THE EFFECT ON SOLAR CELL EFFICIENCY OF VARIATIONS IN GROWTH PARAMETERS.	

1. EFG (MOBILE TYCO)

10 CM WIDE MATERIAL GROWN WITH OR WITHOUT CO₂.

2. UCP (SEMIX)

HIGH EFFICIENCY PROCESS ON MATERIAL FROM INGOT 5464-13C.
MORE SEVERE GETTERING ON MATERIAL FROM INGOT 5464-13C.
10 CM X 10 CM CELLS ON MATERIAL FROM RANDOM SOURCES.

3. HEM (CRYSTAL SYSTEM)

MORE SEVERE GETTERING ON MATERIAL FROM INGOTS 4141C AND 4148.

Summary of Solar Cells Made From EFG 17-200 Series

		Voc (mV)	Jsc (mA/cm ²)	FF (%)	(%)	REMARKS
17-200-1A (4 CELLS)	AVE. S.D. RANGE	495 ±10 480-504	22.5 ±1.5 20.2-23.6	71 ±4 65-73	7.9 ±.7 7.1-8.6	CO ₂ OFF
17-200-113 (2 CELLS)	AVE. S.D. RANGE	515 ±7 510-520	23.0 ±1.2 22.1-23.8	76 ±1 75-77	9.0 ±.5 8.6-9.3	CO ₂ ON
17-200-1D (3 CELLS)	AVE. S.D. RANGE	529 ±5 524-534	24.2 ±.2 24.0-24.3	74 ±3 70-76	9.4 ±.4 9.0-9.7	
17-202-1C (4 CELLS)	AVE. S.D. RANGE	505 ±17 486-516	22.6 ±1.6 20.8-24.2	73 ±1 72-74	8.3 ±.9 7.4-9.2	
17-203-1D (2 CELLS)	AVE. S.D. RANGE	499 ±1 498-500	21.0 ±.3 20.8-21.2	73 ±1 72-74	7.7 ±.3 7.5-7.9	
17-203-1E (2 CELLS)	AVE. S.D. RANGE	487 ±7 482-492	19.8 ±1.4 18.8-20.8	71 ±4 68-74	6.9 ±.2 6.7-7.0	
ACCUMULATIVE AVE OF "CO ₂ ON" CELLS (13 CELLS)		508	22.4	73	8.4	

CZ CONTROL (4 CELLS)	AVE.	583	27.9	78	12.6
	S.D.	±2	±.4	±1	±.2
	RANGE	580-584	27.4-28.3	77-79	12.3-12.9

LARGE-AREA SILICON SHEET TASK

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Summary of Solar Cells Made From 17-175 Series

		VOC (mV)	Jsc (mA/cm)	CFF (%)	(%)	REMARKS
17-175-1A-2 (7 CELLS)	AVE	519	21.2	72	7.9	
	S.D.	± 8	± 1.15	5	$\pm .8$	
	RANGE	504-530	19.8-22.8	62-75	6.4-9.0	
17-175-1A-6 (5 CELLS)	AVE	493	20.1	61	6.2	CO ₂ OFF
	S.D.	± 34	± 1.2	± 16	± 2.1	
	RANGE	434-518	19.4-21.8	61-74	2.7-8.3	
ACCUMULATIVE AVERAGE OF "CO ₂ OFF" CELLS (12 CELLS)		508	20.7	67	7.2	
17-175-1E-52 (8 CELLS)	AVE	539	22.3	73	8.9	
	S.D.	± 12	± 2.1	± 3	± 1.1	
	RANGE	516-554	19.3-24.7	68-77	7.0-10.4	
17-175-1E-56 (6 CELLS)	AVE	505	21.3	59	6.4	CO ₂ ON
	S.D.	± 40.4	± 2.4	± 15	± 2.2	
	RANGE	432-546	17.6-22.6	35-70	3.4-9.1	
ACCUMULATIVE AVERAGE OF "CO ₂ ON" CELLS (14 CELLS)		524	21.9	67	7.8	

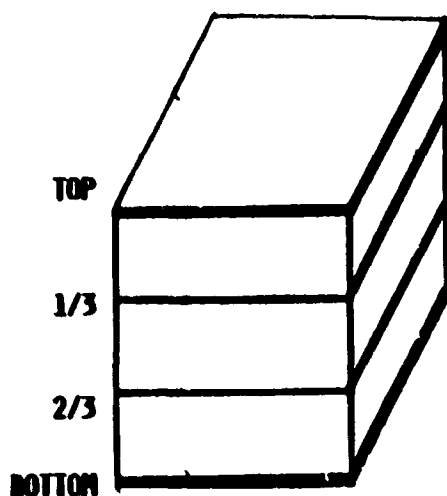
CZ CONTROL (4 CELLS)	AVE	585	28.2	75	12.4
	S.D.	± 2	$\pm .6$	± 3	$\pm .4$
	RANGE	582-586	27.5-28.9	71-78	12.0-12.7

Distribution of J_{SC} on EFG Ribbon 17-175-1E-52

19.3	24.7	22.4	21.2
20.0	24.7	21.8	24.5

growth direction

UCP Ingot No. 5848-13C

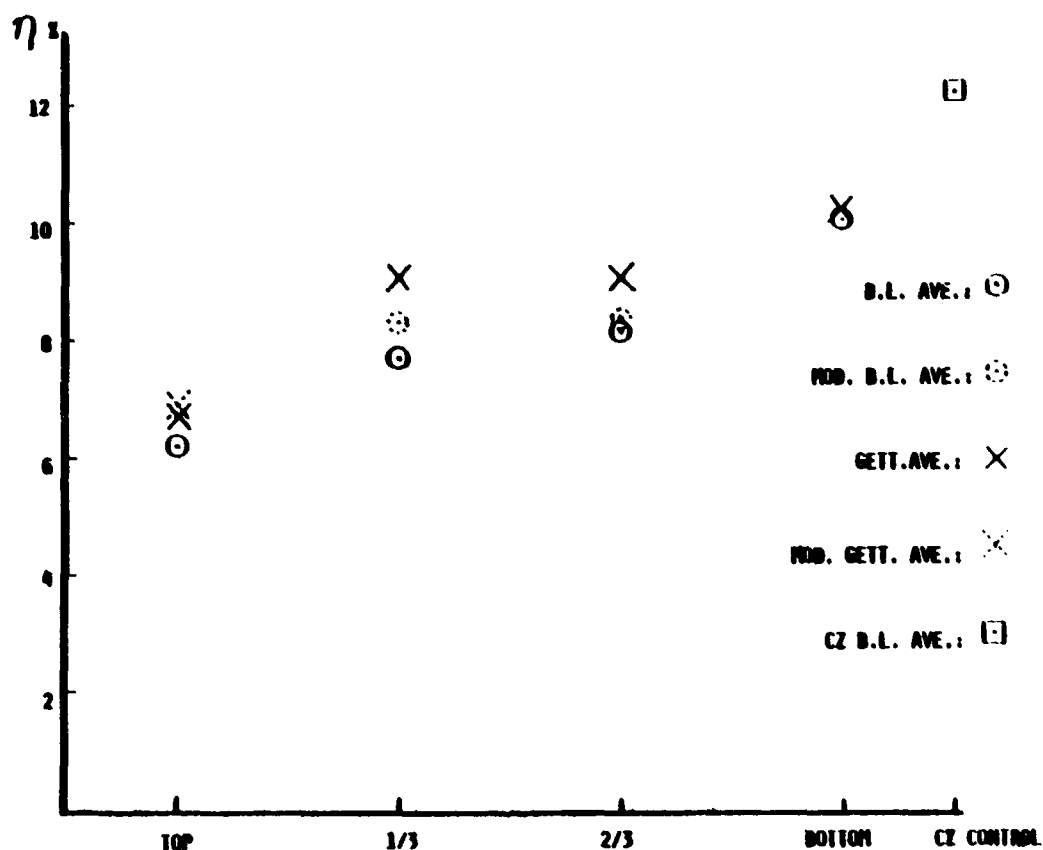


~ 4" x 4" x 4.5"

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

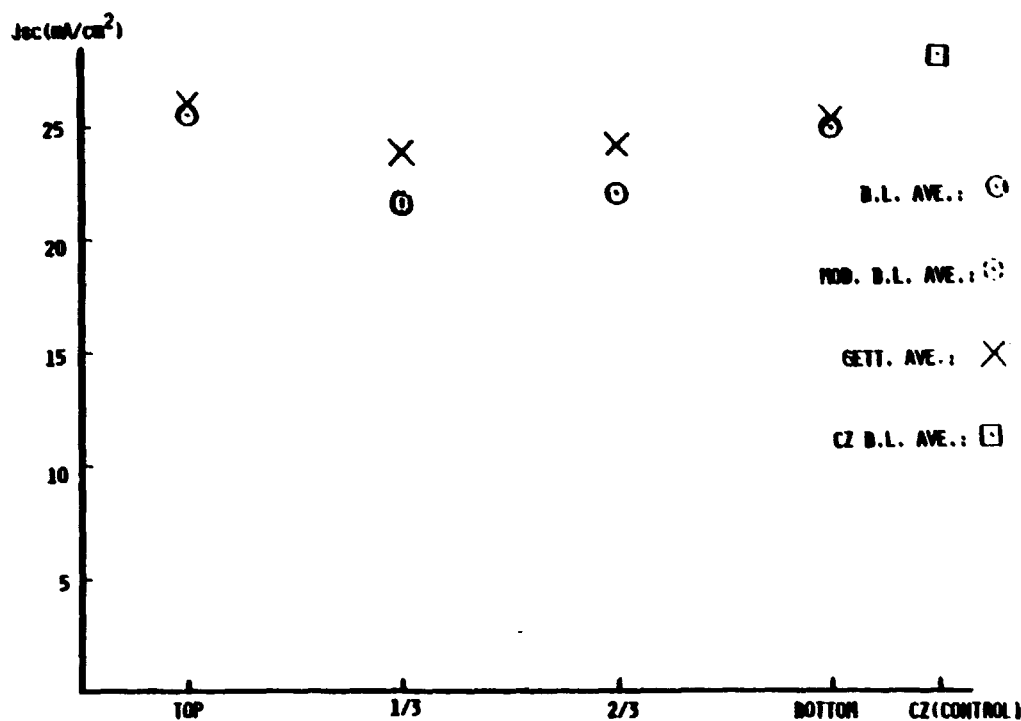
THE CELL'S # AND THEIR RELATIONS TO THE ORIENTATION OF
THE QUARTER INGOT ARE MARKED

Average Efficiency of Different Layers of Ingot 5840-13C



Summary of SJ, BSF and MLAR Cells From UCP Ingot 5848-13C

		Voc (mV)	Jsc (mA/cm ²)	CFP (%)	η (%)
Evaporated Al BSF (UCP - 12 Cells)	A.V.	561	28.7	76	12.2
	S.D.	6	0.6	4	0.8
	RANGE	550-570	27.4-29.4	62-79	9.9-13.1
CZ Control (3 Cells)	A.V.	593	32.6	78	15.1
	S.D.	1	0.2	1	0.2
	RANGE	592-594	32.4-32.8	77-79	14.9-15.3

Average J_{sc} of Different Layers, Ingot 5848-18CSummary of J_{sc} From Cells From More Severe
Gettering Tests (UCP Ingot No. 5848-13C)

Gettering Treatment	Wafer	Ave. J_{sc} (mA/cm ²)	J_{sc} * of The Cell Covered With SiO ₂
None	1/3	22.5	-
	2/3	23.7	-
875°C 1/2 Hr.	1/3	24.6	24.7
	2/3	24.3	24.8
875°C 1 Hr.	1/3	25.5	25.2
	2/3	26.3	24.6
950°C 1 Hr.	1/3	27.0	24.8
	2/3	26.3	25.9
CZ Control (No Treatment)		28.2	-
1050°C 1 Hr.	1/3	26.2	25.9
CZ Control (No Treatment)		28.2	-

* J_{sc} of the cell covered with CVD SiO₂ during gettering diffusion.

Results of Light-Bias Minority Carrier
Diffusion Length Study on Getter

PROCESS	CELLS #	L_{D1} (μm) D.C. DARK	L_{D2} (μm) 0.05 SUN	L_{D3} (μm) 1 SUN	L_{D4} (μm) DARK AFTER LIGHT TURN OFF
BASELINE	2-1	11	16	17	12
8.75°C 1/2 Hr GETTERING	2-4 2-8*	29 29	44 40	60	30
875°C 1 HR GETTERING	2-13 2-9*	159 100	65 60	72	140
950°C 1 HR GETTERING	2-12 2-15*	182 107	89 49	72	167
1050°C 1 HR GETTERING	2-12 2-9*	212 135	116 62	69 81	244 117
CZ CONTROL	1	150	152	156	137

* CELLS WERE COVERED WITH SiO₂ DURING GETTERING DIFFUSION.Summary of Results From 10 x 10 UCP Cells
From Random Sources

	Voc (mV)	Jsc (mA/cm ²)	CFF (%)	(%)
AVE.	553	26.9	72	10.8
S.D.	6	.9	1	.5
RANGE	546-558	25.2-27.6	72-74	10.0-11.3

AREA = 98 cm²

NO. OF CELLS = 6

Comparison of J_{sc} From HEM Cells Gettered for 1 h at 1050°C
With HEM Baseline Cell From Corresponding Area

INGOT #	BASELINE Jsc	GETTER Jsc
41-41C	25.6	26.3
41-48	27.6	28.1

Environmental Isolation Task

C.D. Coulbert, Chairman

A review of the scope of PV module encapsulation technology made available to the industry through the various FSA-supported contracts and studies under the Flat-Plate Collector Research, Engineering Sciences, and Module Performance and Failure Analysis Areas shows it to be very broad (see p. 322). This technology has enabled the PV industry to respond with module designs and hardware with the potential of meeting module cost, performance and life goals. However, a review of these specific technology areas continues to stress the need for continuing module durability research to define module life-limiting degradation mechanisms so they can be quantified, predicted, and corrected. In these early days of PV module development, the great value of durability testing and failure analysis has been to identify design weaknesses; this has been used by industry to develop guidelines by which manufacturers could design and fabricate higher-quality hardware incorporating fault-tolerant design features.

Current FSA research activities are focused on identifying, modeling, and quantifying those long-term degradation mechanisms that would limit the ultimate service life of a PV module. At the same time, research is continuing on encapsulation materials and processes that have the greatest potential of increasing module life and efficiency and effectively reducing module cost.

The following visual presentations summarize significant progress in these areas during the reporting period.

Inasmuch as polymeric encapsulant material properties that may change with long-term field exposure do not necessarily result in a corresponding module damage or failure mode, it has become necessary to organize the failure-analysis process into a more specific set of long-term degradation steps so that material property change can be differentiated from module damage and module failure (see pp. 324-325). These categories allow separation, testing and modeling of the various degradation mechanisms with a clear distinction of which effects interact and which are sequential.

The polymeric aging computer model being developed by the University of Toronto will eventually predict what physical property changes may occur as a function of exposure time and environment. Additional analysis and experimental work are still required to relate polymer property change to module performance loss.

Encouraging development in increasing module performance and life are indicated by the data on module surface treatments for soiling resistance, by improved bonding techniques and primers, by anti-corrosion treatments and by improved polymer stabilizers.

A new photoacoustic technique for very early detection of polymer surface reactions due to aging is being developed and evaluated at JPL. Such techniques are needed if the 20-year potential of modules is to be assessed and validated based on correlating field tests with accelerated tests over a limited number of months of durability testing.

ENCAPSULATION TECHNOLOGY AVAILABLE

JET PROPULSION LABORATORY

C.D. Coulbert

PV MODULE DESIGN	DESIGN ANALYSIS	FAILURE ANALYSIS
<ul style="list-style-type: none"> • PERFORMANCE REQ. • LOADS & HAZARDS • AVAILABLE MATERIALS & PROCESSES • DESIGN ANALYSES & GUIDELINES • LIFE LIMITING MODES 	<ul style="list-style-type: none"> • PERFORMANCE EST. • PHYSICAL DURABILITY ANALYSIS • PREDICTED PROPERTY CHANGES • NOCT/HOT SPOT TEMP. • DESIGN OPTIONS • QUALITY CONTROL REQUIREMENTS • DAMAGE VS. PROPERTY CHANGE • MODULE WEAK LINK 	<ul style="list-style-type: none"> • PERFORMANCE LOSS • WHAT FAILED • WHY FAILED • PROPERTY CHANGE • PROGNOSIS • CORRECTIVE ACTION • PREDICTABILITY • ACCEPTABILITY

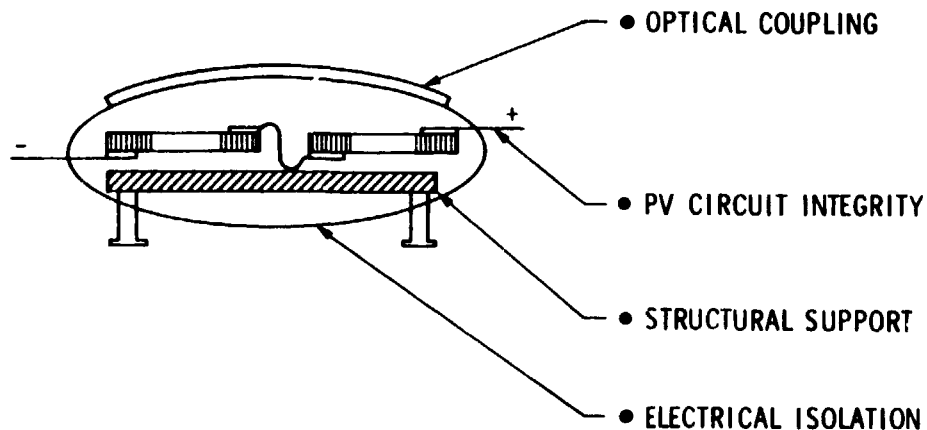
Encapsulation Materials and Processes

- o SURFACE TREATMENTS BASED ON FLUOROCARBONS FOR LOW SOILING MODULE COVERS HAVE REDUCED OPTICAL LOSSES FROM 10% UNTREATED TO 3% OVER A TEN MONTH TEST PERIOD. (TESTING CONTINUES) (SPRINGBORN)
- o NEW CURING AGENTS IDENTIFIED FOR EVA AND EMA TO REDUCE CURING TEMPERATURES AND TIMES. CURING TIMES MAY BE REDUCED FROM 15 MINUTES TO LESS THAN 5 MINUTES (SPRINGBORN)
- o CORROSION RESISTANT COATINGS IDENTIFIED FOR MILD STEEL SUBSTRATE PANELS. TEST SPECIMENS HAVE SURVIVED SALT SPRAY FOR 3000 HOURS WITHOUT DETERIORATION. (SPRINGBORN)
- o EXPERIMENTAL BONDING PRIMER SYSTEMS DEVELOPED AND BEING EVALUATED FOR BONDING EVA AND EMA TO POLYESTER FILMS AND ALSO PRIMERS FOR CORROSION INHIBITION OF MILD STEEL. (DOW CORNING)
- o ION-PLATING AS METHOD FOR NON-FIRED METALLIZATION (TI/AL-Cu) ON SOLAR CELL n-SURFACE DEMONSTRATED. POTENTIAL FEASIBILITY FOR p-SURFACE SHOWN EXPERIMENTALLY. (ITW)
- o TWO NEW POLYMERIZABLE UV STABILIZERS FORMULATED FOR MODULE ACRYLIC COVER FILMS SHOW EXCELLENT UV CUT-OFF SPECTRAL CHARACTERISTICS. (UNIV. OF MASSACHUSETTS).

Encapsulant Material Stability

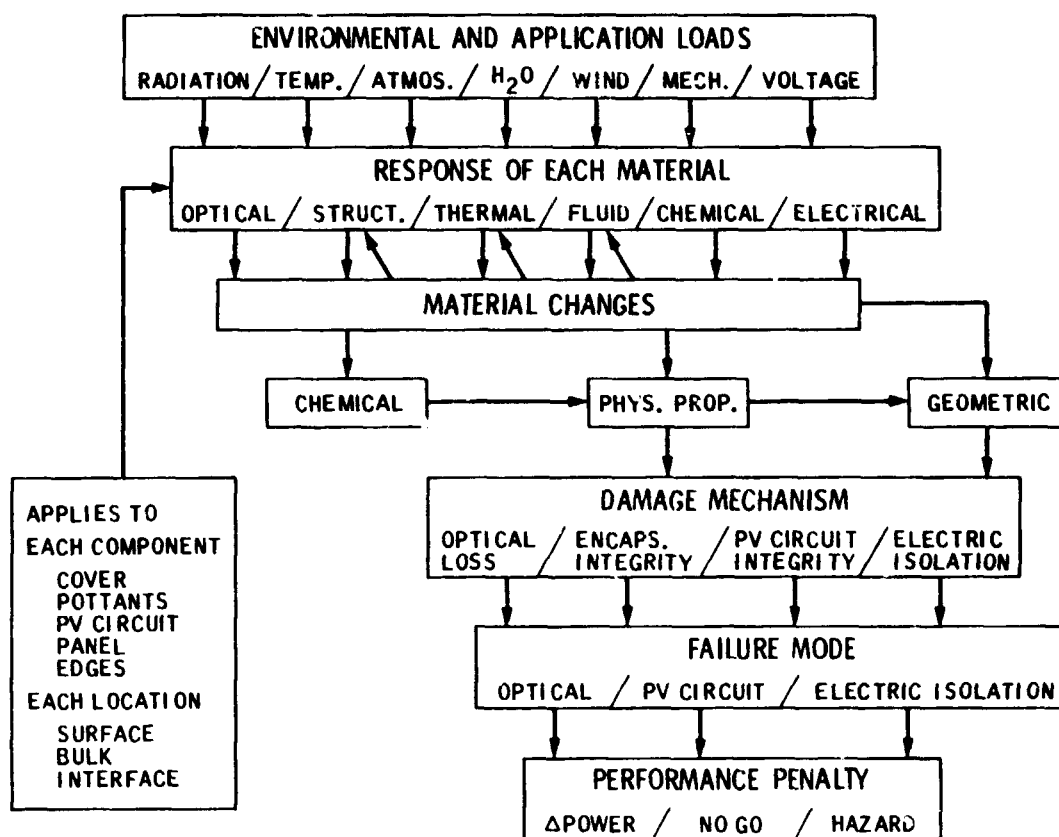
- EVA FORMULATION A9918 HAS SURVIVED > 30,000 HOURS (3.5 YR) OF RS/4 SUNLAMP 55°C EXPOSURE WITHOUT DAMAGE. (SPRINGBORN)
- ADVANCED ENCAPSULANT MATERIALS (EVA, PU, HARDBOARD, CONCRETE, ETC.) IN MINI-MODULE TESTS HAVE ALMOST TWO YEARS OF FIELD EXPOSURE AND PASSED JPL QUAL TESTS. (JPL)
- SUBSTRATE MODULES WITH EVA AND WOOD HARDBOARD SUBSTRATES PASS HAIL IMPACT TESTS. (JPL)
- NEW DIAGNOSTIC TECHNIQUE (LASER PHOTOACOUSTICS) MEASURES POLYMER SURFACE PHOTO OXIDATION AND CORRELATES 60-DAY FIELD EXPOSURE WITH 10-HOUR LAB TESTS. (JPL)
- FULL-SIZE MODULE TEST FACILITY FOR ACCELERATED UV THERMAL TESTING COMPLETED AND INITIAL TESTS IN PROCESS. (JPL)
- MATERIAL PROPERTY (MOLECULAR WEIGHT, STRENGTH, TOUGHNESS AND STABILITY) PREDICTION BY COMPUTER MODEL OF POLYMER MOLECULAR STRUCTURE DEVELOPED AND DEMONSTRATED. (ROCKWELL SCIENCE CENTER)
- MODULE RESPONSES TO ENVIRONMENT AS A FUNCTION ENCAPSULANT PROPERTIES AND THICKNESSES PREDICTABLE BY COMPUTER MODELING. REDUCED VARIABLE MASTER CURVES DEVELOPED FOR CELL STRESS PREDICTION FOR WIND AND TEMPERATURE. (SPECTROLAB AND JPL)
- COMPUTER MODEL OF EVA PHOTODEGRADATION YIELDS DEGRADATION PRODUCTS VS TIME. LONG INCUBATION PERIOD INDICATED (5 - 10 YEARS). (UNIV. OF TORONTO)
- REPORT ON EXPERIMENTAL PHOTOTHERMAL CHARACTERIZATION OF CANDIDATE POTANTS AND COVER FILM MATERIALS EXPOSED TO UV AND AIR UP TO 105°C COMPLETED AND IN PUBLICATION. (JPL).

Encapsulation Requirements



WHEN ONE OF THESE IS VIOLATED
YOU HAVE DAMAGE AND POTENTIAL FAILURE

PV Module Failure Analysis Sequence



Durability Analysis Categories

DESIGN DETAILS								MT'L & CONFIG.
EXPOSURE	QUAL	FIELD	ACCEL / TIME					TEST CONDITIONS
LOADS	RAD	TMP	ATM	H2O	WND	MEC	VLT	INTENSITY/TIME
COMPONENT	COV	POT	PAN	EDG	PVC			OR MATERIALS
LOCALITY	SRF	BLK	INT					WHICH OR WHERE
RESPONSE	OPT	STR	THM	FLD	CHM	ELC		QUANTITATIVE
CHANGE	CHM	PHY	GEO					MEASURABLE/VISIBLE
DAMAGE	OPT	ENC	PVC	ISO				INTEGRITY
FAILURE	OPT	PVC	ISO					OPERATIONAL
PENALTY	PWR	NOG	HZD					VALUE LOSS

Example

DESIGN DETAILS	SENSOR TECH BLK 11							CONF, MTL & FLAWS
EXPOSURE	BATTELLE TFST (ACCEL) / TIME 4 MONTHS 250 CYCLES ~15/95 SO ₂ ~95% BIAS							TEST CONDITIONS
LOADS	(IMP) (ATM) (H2O) (VLT)							INTENSITY/TIME
COMPONENT	(POT) (PAN) (PVC) (CIRCUIT INTERCONNECTS)							OR MATERIALS
LOCALITY	(SRF) (BLK) (INT) (BLK) (BLK)							WHICH OR WHERE
RESPONSE	(OPT) (STR) (THM) (FLD) (CHM) (THM) (THM) (STR)							REVERSIBLE/QUANT
CHANGE	(PHY) (PHY) (GEO) (PHY)							MEASURABLE/VISIBLE
DAMAGE	(PVC) (PVC) (NOG)							INTEGRITY VIOLATED
FAILURE	(PVC) (NOG)							OPERATIONAL
PENALTY	(NOG)							VALUE LOSS

MATERIAL RESEARCH AND EVALUATION

SPRINGBORN LABORATORIES, INC.

Candidate Pottant Materials

SHEET LAMINATION GRADES:

- . EMA
- . EVA

CASTING SYRUPS:

- POLYBUTYL ACRYLATE
- . ALIPHATIC POLYURETHANE

PHASES:

- . INDUSTRIAL EVALUATION GRADE
- . TECHNOLOGY READINESS STAGE

CURRENT WORK:

- . ADVANCED CURE SYSTEMS
- . THERMAL AGING EVALUATION
- . ADVANCED STABILIZATION

Pottants

INVESTIGATION OF PEROXIDE CURING AGENTS:

- . CURE POLYMER TO HIGH GEL CONTENTS
- . CURE IN THE RANGE OF 120°C TO 160°C
WITH NO PREMATURE "SCORCH" AT 110°C
MUST BE SOLUBLE IN THE RESIN AND NON-
VOLATILE TO PREVENT LOSS
- . MUST NOT SENSITIZE THE AGING OF THE
RESIN (NON-AROMATIC)
MUST BE COMPATIBLE WITH THE STABILIZERS
AND OTHER INGREDIENTS
- . MUST NOT PRODUCE CHEMICALLY ANTAGONISTIC
BYPRODUCTS OR RESULT IN BUBBLING

GENERAL MECHANISM:

1. $RO-OR \xrightarrow{\Delta} 2 RO^{\bullet}$
2. $P-H + RO^{\bullet} \longrightarrow P^{\bullet} + ROH$
3. $2P^{\bullet} \longrightarrow P-P$ (CROSSLINK)

- TERTIARY HYDROGENS ON THE POLYMER BACKBONE MOST
READILY ABSTRACTED.
- CURING MUST BE CONDUCTED IN THE ABSENCE OF OXYGEN
TO BE EFFECTIVE AND TO PREVENT OXIDATION OF THE RESIN.

Pottant Compounds

ADVANCED CURE SYSTEMS IN EVA

CURE TEMP.	TIME REQUIRED FOR 70% GEL CONTENT				
	<u>120</u>	<u>130</u>	<u>140</u>	<u>150</u>	<u>160</u>
LUPEPSOL 101	N/A	N/A	45	15	6
LUPERSOL 99	30	20	12	8	2
LUPERSOL 331-80B	15	10	5	2	2
LUPERSOL TBEC	30	10	4	2	1

ALL PEROXIDES COMPOUNDED INTO STANDARD FORMULA,
A9918.

NO CURE OCCURS AT 110°C WITH ANY PEROXIDE: SHOULD
SURVIVE EXTRUSION OK.

ADVANCED CURE SYSTEMS IN EMA

	TIME REQUIRED FOR 50% GEL CONTENT		
	<u>130°C</u>	<u>140°C</u>	<u>150°C</u>
LUPERSOL 101	N/A	60	30
LUPERSOL 99	30	15	5
LUPERSOL 331-80B	15	10	5
LUPERSOL TBEC	25	5	< 2

ALL PEROXIDES TESTED IN STANDARD FORMULA
NO. 13439.

NO CURE AT 110°C IN ANY FORMULATION: SHOULD
SURVIVE EXTRUDER OK.

ENVIRONMENTAL ISOLATION TASK

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NEW CURING AGENTS FOR EVA AND EMA

	<u>% ACTIVE</u>	<u>ONE HOUR HALF-LIFE TEMPERATURE</u>	<u>FLASH POINT (VOLATILITY)</u>
LUPERSOL 101	100%	138°C	43°C
LUPERSOL 331-80B	75%	111°C	40°C
LUPERSOL 99	75%	118°C	77°C
LUPERSOL TBEC ^{A.}	100%	120°C	101°C

- . LUPERSOL TBEC CURING AGENT OF CHOICE:
- . HIGHEST CURING EFFICIENCY
- . 100% ACTIVE, NO DILUENT
- . LOWEST VAPOR PRESSURE

TECHNOLOGY VOIDS:

- . PLANT EXTRUSION PUNS
- . SHELF LIFE DETERMINATION
- . COMPATABILITY WITH ADHESION SYSTEM

A. LUPERSOL TBEC IS O,O-T-BUTYL-O-(2-ETHYL HEXYL) PEROXY
CARBONATE

ENVIRONMENTAL ISOLATION TASK

ETHYLENE VINYL ACETATE, A9918
(COMMERCIAL FORMULATION)

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CAVEAT:

- . CURING AGENT (PEROXIDE) IS SLIGHTLY VOLATILE
KEEP THE EVA IN ROLL FORM WHERE LOSS IS INHIBITED
- . DO NOT USE CUT SHEET WHICH HAS BEEN OPENLY EX-
POSED FOR OVER ONE DAY

ROLLS APPEAR TO HAVE INDEFINITE SHELF LIFE.

NEED TO DETERMINE PEROXIDE LOSSES VERSUS TIME
AND STORAGE CONDITIONS

Butyl Acrylate Casting Syrup

FORMULA: BA 13870

- . INDUSTRIAL SAMPLES AVAILABLE -
(LABORATORY PROCESS)

	CURE TIME GUIDE				
	25°C	35°C	50°C	60°C	70°C
TIME TO ONSET OF CURE (MINUTES)	STABLE ^(A)	STABLE ^(A)	60	25	6.5

- . PILOT PLANT QUANTITIES
 - . INITIATOR AND DATA SHEET SUPPLIED WITH
EACH REQUEST
 - . PRIMER: TENTATIVE RECOMMENDATION
SPRINGBORN 14588
(DOW CORNING Z-6020 WITH TETRAETHYL
SILICATE)
ALSO PROVIDED WITH REQUEST
- A. STABLE AT LEAST ONE WEEK, REFRIGERATION SUGGESTED.

Aliphatic Urethane Encapsulant

FORMULA: Z-2591

- . AVAILABLE - DEVELOPMENT ASSOCIATES, INC.
NORTH KINGSTOWN, R.I.
- . COST: APPX. \$3.00 PER POUND
(MIXED SYSTEM)
- . CONTACT: MR. BUD NANNIG
- . PRIMER: . TENTATIVE RECOMMENDATION
DOW CORNING Z-6020
(10% SOLUTION IN METHANOL)
. BAKE PRIMERS ALSO
AVAILABLE - DEVELOPMENT
ASSOCIATES, INC.

ENVIRONMENTAL ISOLATION TASK

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RS/4 Exposures

POTTANT COMPOUNDS:

POTTANT	HOURS	% PROPERTY RETAINED	
		TENSILE	ELONGATION
URETHANE Z-2591	4,000	82%	91%
EMA 23439	7,600	120%	119%
EMA 11877	15,000	130%	117%
EMA 2205 (UNCOMPOUNDED)	15,000	5%	5%
		REMOVED	
BUTYL ACRYLATE 13870	7,600	60%	88%
EVA W/UV-2098	JUST STARTED		
EVA W/5-VINYL TINUVIN REACTED IN	15,000	77%	78%

REFERENCE:

POLYETHYLENE UNSTABILIZED	500	10%
POLYPROPYLENE UNSTABILIZED	500	0%

ENVIRONMENTAL ISOLATION TASK

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OUTER COVER AND BACK COVER FILMS:

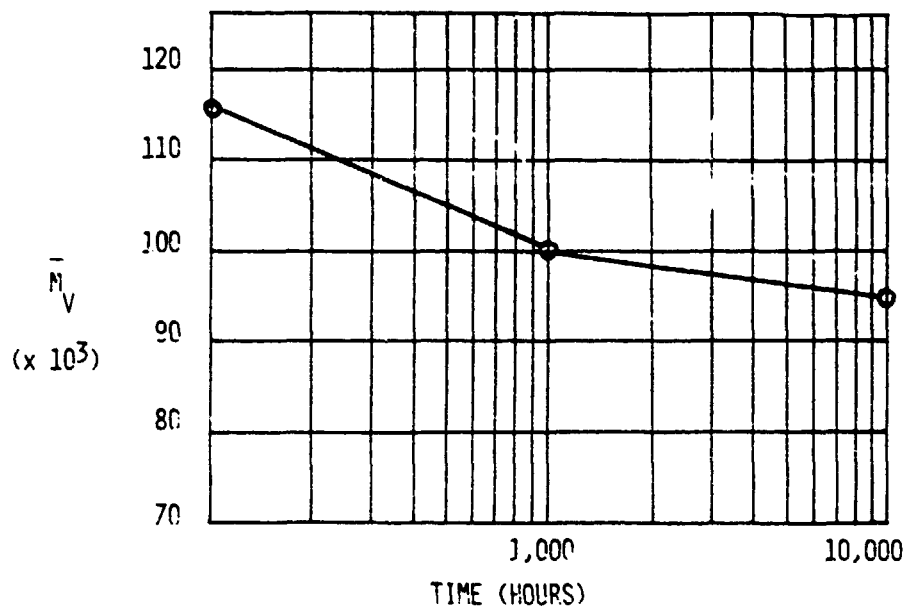
<u>OUTER COVER FILM</u>	<u>HOURS</u>	<u>% PROPERTY RETAINED</u>	
		<u>TENSILE</u>	<u>ELONGATION</u>
ACRYLAR X-22417	12,000	54%	100%
TEDLAR 100 RG 30 UT	14,000	94%	98.5%
TEDLAR 4662	10,800	140%	38%
TEDLAR 05VT (W/VINYL TINUVIN)	10,800	67%	1%
FLUOREX-A	10,800	70%	30%
<u>BACK COVER FILMS</u>			
TEDLAR 200 BS 30 WH	10,800	98%	93%
SCOTCHPAR 20CPW	6,600	95%	74%
KORAD 63000	6,600	94%	71%

TEDLARS (BOTH CLEAR AND PIGMENTED)
APPEAR TO BE MOST STABLE.

"ACRYLAR" BIAXIALLY ORIENTED

ACRYLIC FILM

(3M X 22417)

DECREASE IN VISCOSITY AVERAGE MOLECULAR WEIGHT WITH
EXPOSURE TIME.MOLECULAR WEIGHT DECREASES FROM 116,000 TO 94,800 IN
10,000 HOURS TIME.

ENVIRONMENTAL ISOLATION TASK

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EVA POTTANT
(NO COVER FILM)

- . CLEAR STABILIZED EVA EXPOSED 30,000 HOURS,
LITTLE CHANGE.

	TOTAL INTEGRATED <u>TRANSMISSION</u> (%)	ULTIMATE* <u>ELONGATION</u> (%)	TENSILE* <u>STRENGTH</u> (PSI)
CONTROL	91	510	1890
EXPOSED 30,000 HRS.	90	480	1450
% CONTROL	99%	94%	77% ^A

UNSTABILIZED ELVAX 250 (EVA) BECOMES SOFT, TACKY, -
LOSES PHYSICAL PROPERTIES IN LESS THAN 1,000 HOURS.

*ASTM D-638

- A. FIRST SIGN OF CHANGE NOTICES THROUGHOUT EXPOSURE
PERIOD

Substrate Materials

CURRENT CANDIDATES

<u>MATERIAL</u>	<u>¢/FT²</u>	<u>\$/M²</u>
COLD ROLLED MILD STEEL, 28 GAUGE	15.5	1.67
SUPER DORLUX HARDBOARD (MASONITE CORP.)	14.0	1.51
DURON TEMPERED HARDBOARD (US GYPSUM COMPANY)	14.5	1.56

- . SUBSTRATE ALLOCATION APPROX. 70¢/FT²
- . COST INCREMENT WILL APPEAR FOR PROTECTIVE
TREATMENT

ENVIRONMENTAL ISOLATION TASK

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PROTECTIVE COATINGS OR TREATMENTS REQUIRED FOR LONG OPERATING
LIFE IN OUTDOOR ENVIRONMENT

POSSIBILITIES:

- . ENCAPSULATE ENTIRE SUBSTRATE WITH WEATHERABLE POTANT
- . LAMINATION WITH OCCULSIVE FOIL:^A
E.G.: "HOT-FOIL" TREATMENT
(ALUMINUM FOIL WITH HOT MELT ADHESIVE)
- . LAMINATE WITH ORGANIC FILMS
- . COATING WITH WEATHERABLE ENAMEL^B OR PAINT
- . COMBINATIONS OF THESE
- . CHEMICAL MODIFICATION (WOOD)

A. TECHNIQUE BEING DEVELOPED BY U.S. GYPSUM AND OTHERS.

B. RECOMMENDATIONS FROM:

DOW CORNING CORPORATION
DEXTER - MIDLAND CORPORATION
STEEL STRUCTURES PAINTING
COUNCIL (SSPC)

TESTING

TEST "MODULES" PREPARED WITH COATED STEEL PANEL, BUTYL SEALANT
AND GASKET

Corrosion Experiments

MILD STEEL SUBSTRATES
SALT SPRAY EXPOSURE
(ASTM B-117)

<u>COATING</u>	<u>ADHESIVES</u>	<u>HOURS</u>	<u>CONDITIONS</u>
ACRYLAR	ACRYLIC	2,000	R
SCOTCHPAR	ACRYLIC	2,000	R
ALUM. FOIL	ACRYLIC	1,500	R
KORAD (WHITE)	ACRYLIC	2,000	R
EVA	SILANE	1,500	R
CLEAR KORAD	ACRYLIC	2,000	R
ACMITITE	ACRYLIC	2,500	R
WHITE TEDLAR	ACRYLIC	2,000	R
302 STAINLESS	ACRYLIC	2,500	R
EVA/SCOTCHPAR	SILANE	4,500	I
EVA/STAINLESS	SILANE	2,500	R
EVA/TEDLAR	SILANE	2,500	R
SCOTCHCLAD	NONE	2,000	R
EVA	CHROMATE/SILANE	4,000	II
VINYLDENE/FLUORIDE	EPOXY	3,500	III
SILICONE/POLYESTER	EPOXY	3,100	II
ACRYLIC AUTO TOPCOAT	EPOXY	3,100	III

I NO OBSERVABLE CHANGE
 II SOME SIGNS OF DETERIORATION (CORROSION, DELAMINATION)
 III NOTICEABLE DETERIORATION
 R SPECIMEN FAILED, REMOVED

MILD STEEL SUBSTRATES
OUTDOOR EXPOSURE, ENFIELD, CT.

<u>COATING</u>	<u>ADHESIVES</u>	<u>HOURS</u>	<u>CONDITIONS</u>
ACRYLAR	ACRYLIC	4,500	II
SCOTCHPAR	ACRYLIC	4,500	II
ALUM. FOIL	ACRYLIC	4,500	I
KORAD (WHITE)	ACRYLIC	4,500	II
EVA	SILANE	4,500	II
CLEAR KORAD	ACRYLIC	1,500	R
ACMITITE	ACRYLIC	4,500	I
WHITE TEDLAR	ACRYLIC	4,500	I
302 STAINLESS	ACRYLIC	4,500	II
EVA/SCOTCHPAR	SILANE	4,500	I
EVA/STAINLESS	SILANE	4,500	II
EVA/TEDLAR	SILANE	4,500	II
SCOTCHCLAD	NONE	4,500	II
EVA	CHROMATE/SILANE	4,000	II
VINYLDENE FLUORIDE	EPOXY	3,400	II
SILICONE/POLYESTER	EPOXY	3,100	II
ACRYLIC AUTO TOPCOAT	EPOXY	3,100	II

- I NO OBSERVABLE CHANGE
 II SOME SIGNS OF DETERIORATION (CORROSION, DELAMINATION)
 III NOTICEABLE DETERIORATION
 R SPECIMEN FAILED, REMOVED

Hardboard Protection Experiments

"SUPER DORLUX" - MASONITE CORPORATION

"MODULES" PREPARED WITH BUTYL EDGE SEAL AND
GASKET - SIX MONTHS OUTDOORS,
ENFIELD, CONNECTICUT

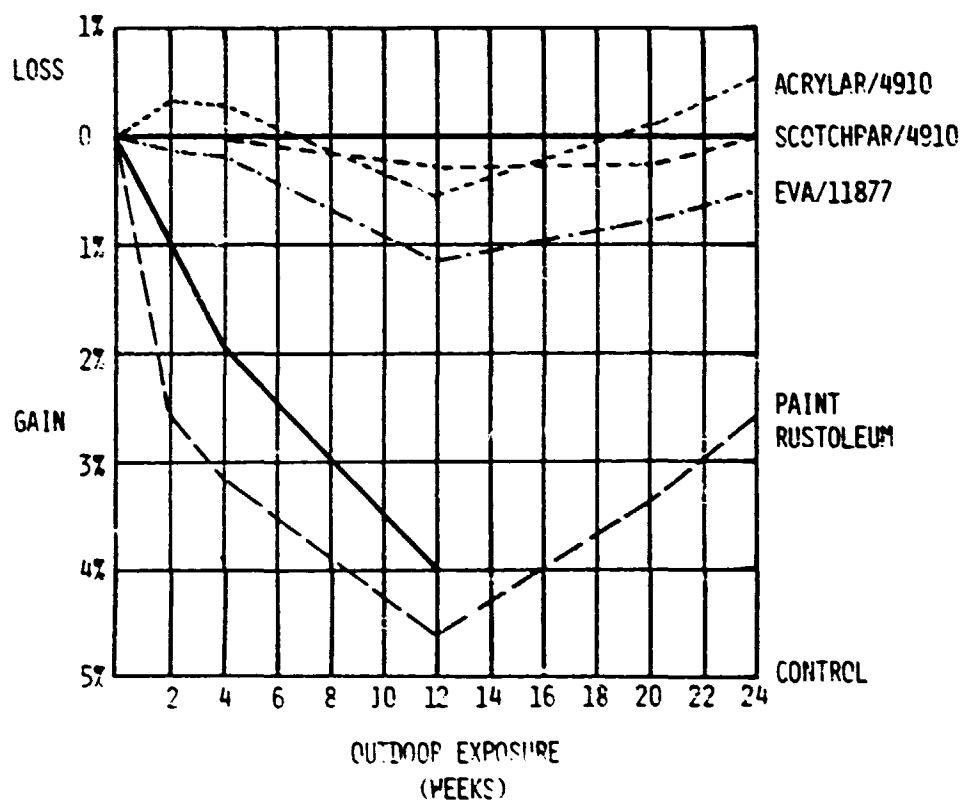
COATING	ADHESIVE	% CHANGE MODULE	% CHANGE HARDBOARD
ACRYLAR	3M 4910	-.40	-.53
KORAD 63000	3M 4910	-.58	-.75
PAINT (RUSTOLEUM)	-	+1.98	+2.57
302 STAINLESS	3M 4920	-.03	-.05
ALUM. FOIL	3M 4910	+.07	+.09
SCOTCHPAR 20CP	3M 4910	+.03	+.05
EVA 99J8	A 11861	+.36	+.53
TEDLAR, WHITE	68070	-.26	-.34
MELAMINE "SHOWER COATING"			
AND EVA 9918 WITH A 11861	-	+2.56	+3.26
HARDBOARD	UNCOATED	-	+3.36

- . NO SIGNS OF DELAMINATION OR EDGE SEAL DETERIORATION
- . RAINFALL, 12.6 INCHES TOTAL
- . BEST PERFORMANCE TO DATE WITH METAL FOIL COVERS
- . BEST ORGANIC FILM, SCOTCHPAR POLYESTER

ENVIRONMENTAL ISOLATION TASK

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"SUPER DORLUX" MODULES PREPARED
WITH BUTYL EDGE SEAL AND GASKET



Soiling Effects

DECAY IN OPTICAL TRANSMISSION
SITE: ENFIELD, CONNECTICUT

MATERIAL	% TRANSMISSION ^A		
	CONTROL	4 WEEKS	8 WEEKS
PYREX GLASS	92	90	90
SODA LIME GLASS	87	84	87
TEDLAR 100B630UT	84	72	77
RTV 615	79	65	65
Q1-2577	74	65	64
SYLGARD 184	82	81	54

A. DIRECT TRANSMISSION FROM 350 NM TO 900 NM.

JPL SOILING THEORY SUGGESTS THAT SOIL RESISTANT
SURFACES HAVE THE FOLLOWING PROPERTIES

HIGH SURFACE HARDNESS

HYDROPHOBIC

OLEOPHOBIC

ION FREE

LOW SURFACE ENERGY

SMOOTH

Antisoiling Experiments

SURFACE UNDER INVESTIGATION:

SUNADEX GLASS

3M ACRYLIC FILM, X-22417

TEDLAR 100BG30UT - DU PONT

SURFACE TREATMENTS UNDER INVESTIGATION:

3M FLUOROSILANE TREATMENT L-1668^A

PERFLUORODECANOIC ACID BASED COATING^A
DOW CORNING E-3820

OWENS ILLINOIS GLASS RESIN 650

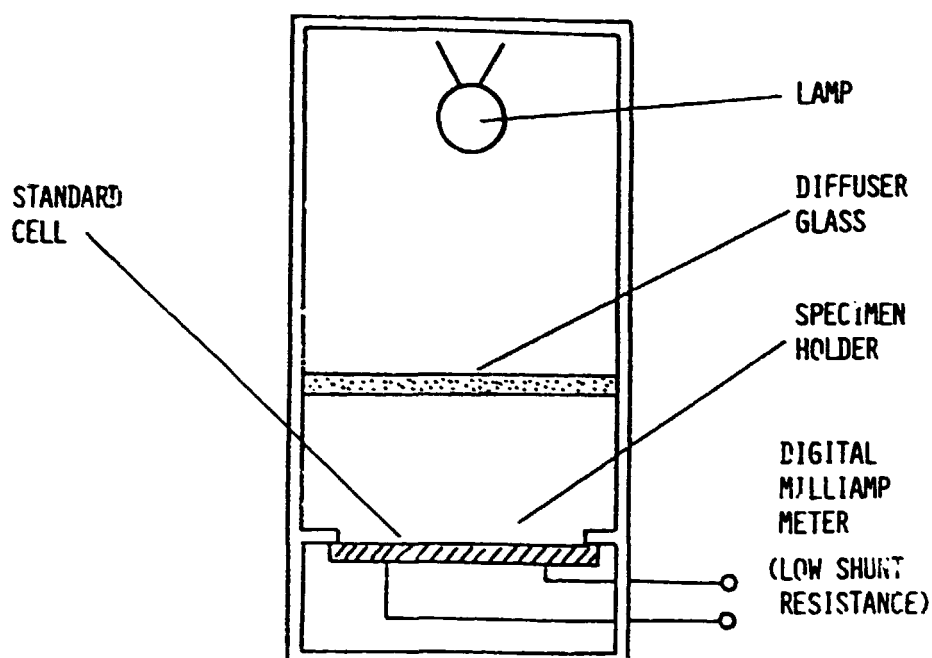
GENERAL ELECTRIC SHC - 1000

ROHM & HAAS WL-81 ACRYLIC COATING

- A. ALSO USED WITH OZONE TREATMENT TO COUPLE TO
ORGANIC SURFACES.

Antisoiling Program

SHORT CIRCUIT MEASUREMENT DEVICE



$$\frac{\text{CURRENT W/SPECIMEN}}{\text{SHORT CIRCUIT CURRENT}} \times 100 = \% \text{ CHANGE IN SHORT CIRCUIT CURRENT}$$

Antisoiling Test Results

TEN MONTH EXPOSURE
ENFIELD, CONN.

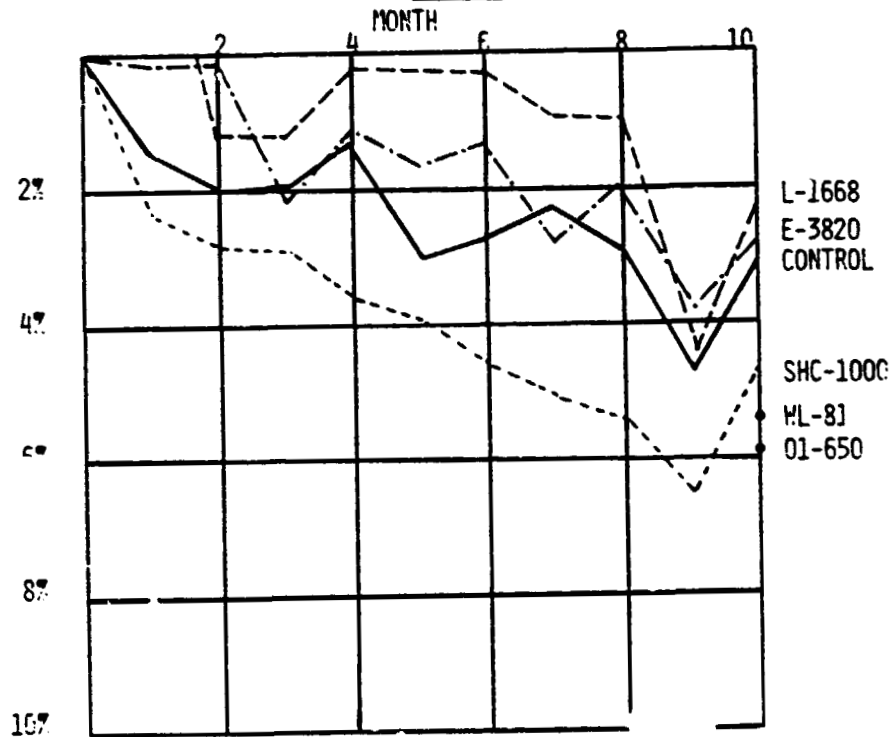
TREATMENT	SUNADEX		ACRYLIC X-22417		TELLAR 100 BG 30 UT	
	INITIAL	Δ %	INITIAL	Δ %	INITIAL	Δ %
CONTROL NO TREATMENT	90.5	-3.2	84.0	-10.8	87.7	-8.8
L-1668	89.7	-2.3	80.3	-6.6	88.4	-5.3
L-1668/OZONE	A.	A.	84.5	-6.1	88.1	-5.0
PFDA E-3820	90.0	-2.7	80.0	-6.8	86.0	-3.8
PFDA E-3820/OZONE	A.	A.	84.1	-4.9	86.0	-6.4
GLASS RESIN 650	91.0	-5.7	81.1	-7.4	89.0	-6.5
SHC - 1000	91.9	-4.5	82.1	-7.6	89.0	-5.6
WL-81	90.7	-5.1	83.6	-6.3	87.7	-5.2

A. NOT PREPARED

Antisoiling Experiments

TEN MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{sc} WITH STANDARD CELL
TREATED SUNADEX GLASS



BEST TREATMENT, L-1668

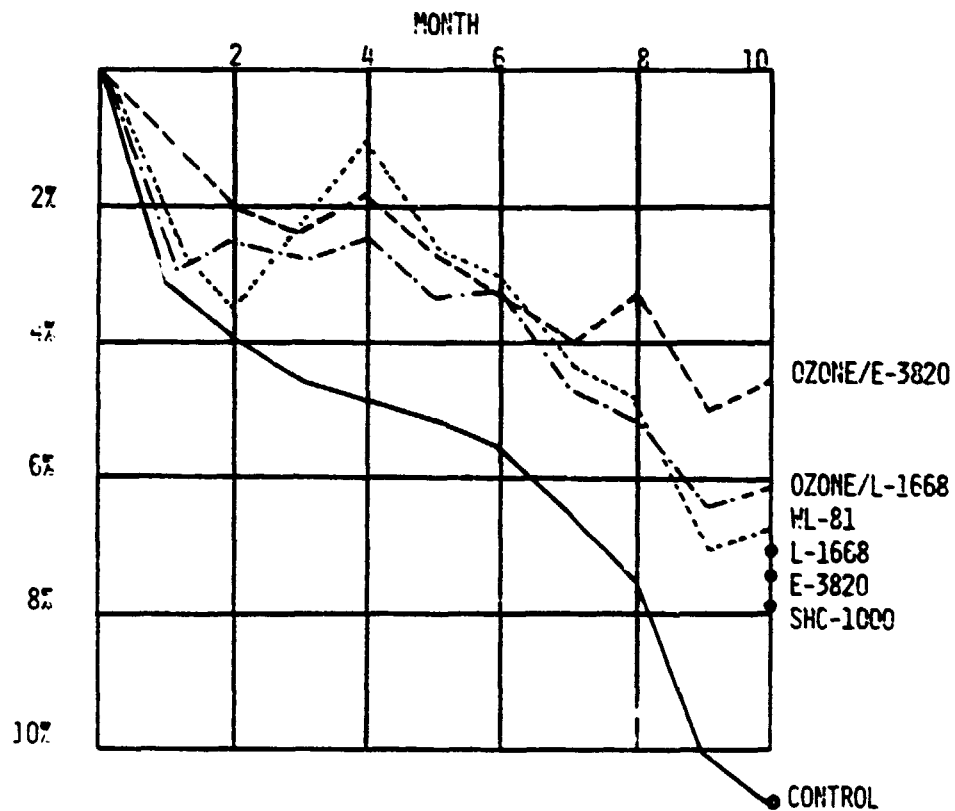
ENVIRONMENTAL ISOLATION TASK

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TEN MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL

TREATED ACRYLAR
(SUPPORTED ON GLASS)



BEST TREATMENT, OZONE WITH
E-3829 (FLUOROSILANE)

ENVIRONMENTAL ISOLATION TASK

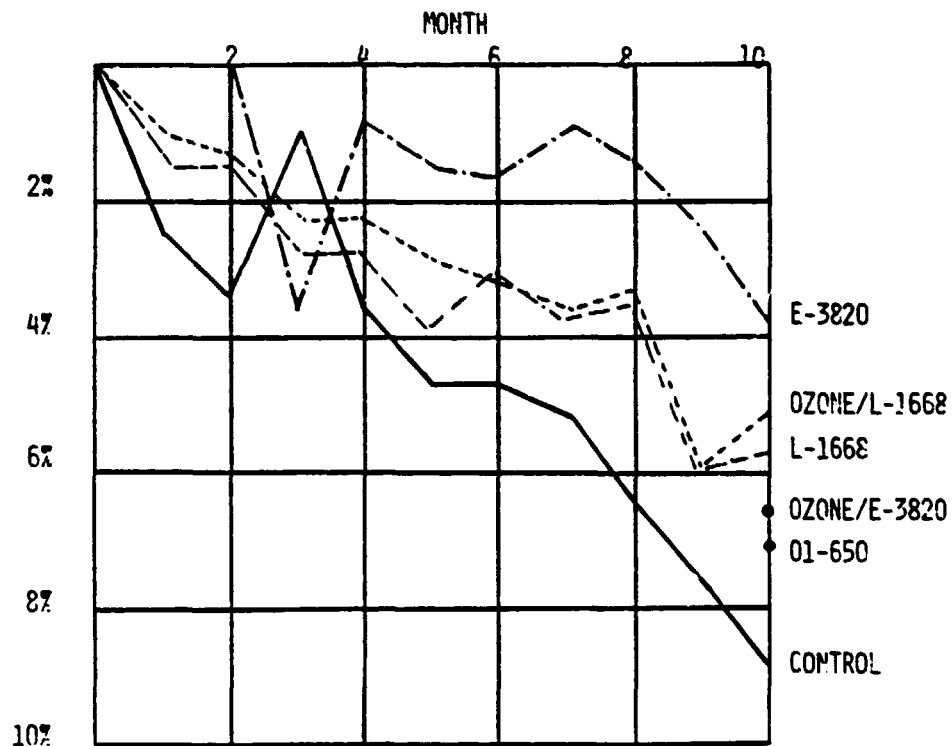
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TEN MONTHS EXPOSURE, ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL

TREATED TEDLAR 100B6300UT

(SUPPORTED ON GLASS)



BEST TREATMENT, E-3820

ENVIRONMENTAL ISOLATION TASK

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GENERAL OBSERVATIONS:

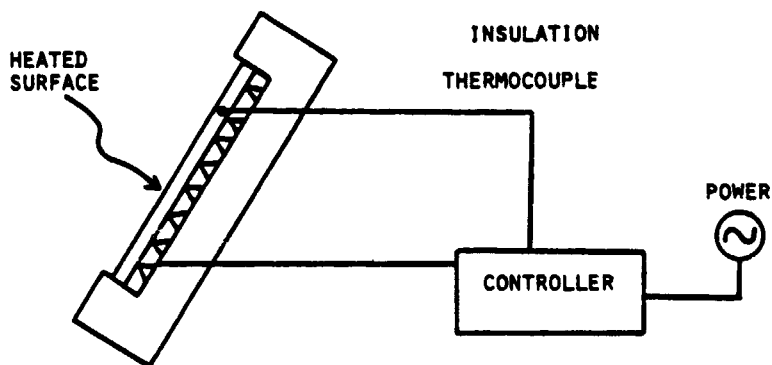
- . SUNADEX HAS BEST CONTROL VALUES (-3.0%)
- . SUNADEX: BEST COATING, L-1658 (-0.5%)
- . TEDLAR: BEST COATING, E-3820 (-1.5%)
- . ACRYLAR: BEST COATING, OZONE + E-3820 (-2.4%)
- . GOOD CORRELATION WITH NATURAL "CLEANING" CONDITIONS

NEW MATERIALS:

- . NEW FLUOROSILANE (SPRINGBORN):
PERFLUORO-OCTYL TRIETHOXY SILANE
- . REACTIVE POLYMER SURFACE TREATMENT (SPRINGBORN):
PERFLUOROBUTYL ACRYLATE COPOLYMERIZED
WITH DOW CORNING Z-6030 SILANE

Accelerated Aging Test Program: Outdoor Photothermal Aging

- . USE NATURAL SUNLIGHT, AVOIDS SPECTRAL DISTRIBUTION PROBLEMS WITH ARTIFICIAL LIGHT SOURCES
- . USES TEMPERATURE TO ACCELERATE THE PHOTOTHERMAL REACTION
- . INCLUDES DARK CYCLE REACTIONS
- . INCLUDES DEW/RAIN EXTRACTION
- . SILICONE RUBBER HEATERS - IN OPERATION ONLY DURING SUNLIT HOURS



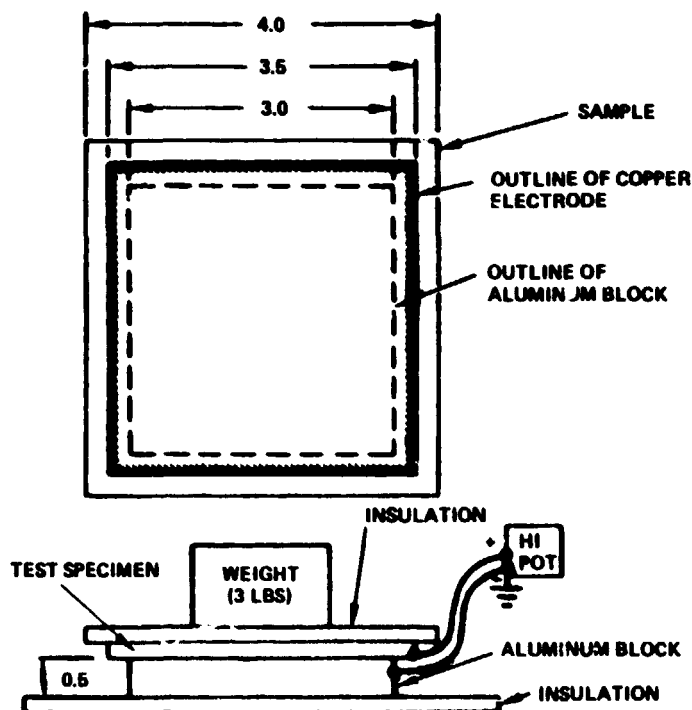
- . TEMPERATURES OF INTEREST,
70°, 90°, 110° C
- . TEST MATERIALS:
 - 4 POTTANTS: EVA, EMA, BA, PU
 - 3 OUTER COVERS: SUNADEx, TEDLAR, ACRYLIC
 - COMBINATIONS OF POTTANTS/OUTER COVERS
- . TESTS:
 - DIELECTRIC STRENGTH
 - CHEMICAL INERTNESS (COPPER CORROSION)
 - OPTICAL TRANSMISSION
 - STANDARD CELL OUTPUT
 - GEL CONTENT
 - YOUNG'S MODULUS
 - TENSILE STRENGTH
 - ULTIMATE ELONGATION
- . DUPLICATE SPECIMENS - PHOENIX AND FLORIDA

ENCAPSULANT DESIGN ANALYSIS AND VERIFICATION

SPECTROLAB, INC.

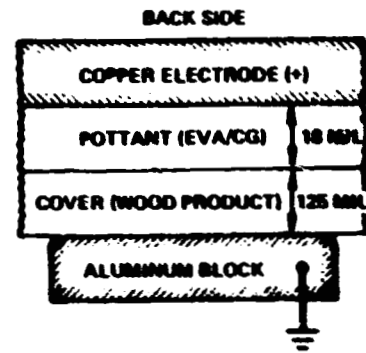
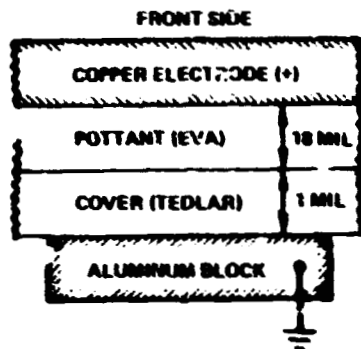
C.P. Minning (Hughes Aircraft Co.)

Electrical Test Setup

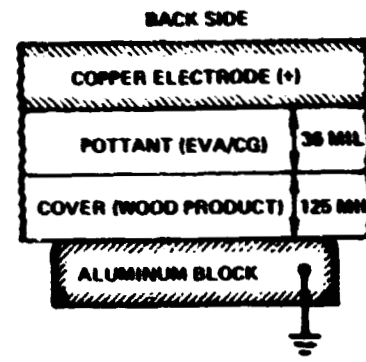
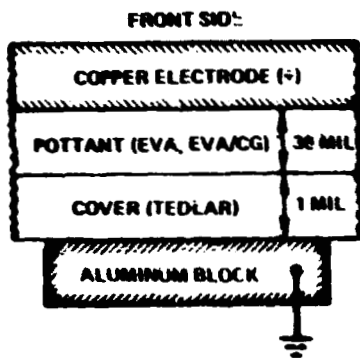


ENVIRONMENTAL ISOLATION TASK

Electrical Isolation Models (Typical)

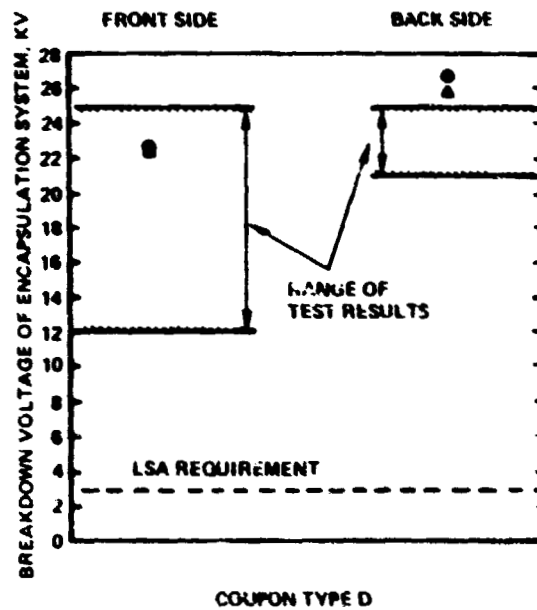
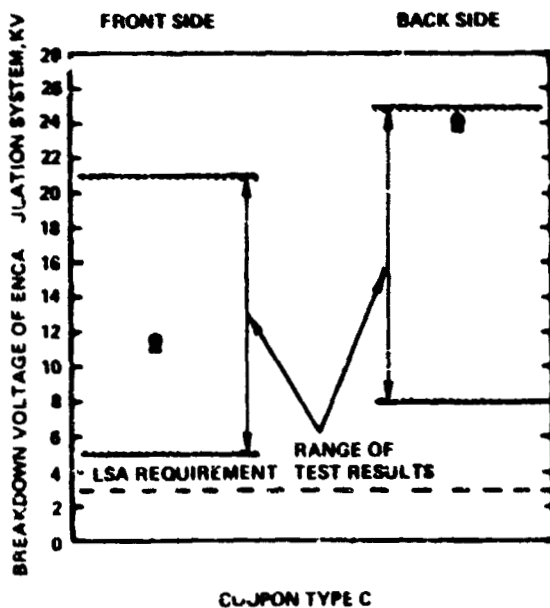


TYPE C COUPONS



TYPE D COUPONS

Electrical Isolation Test Results



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Figure 1 consists of two views of the test cell: a Plan View and an Edge View. The Plan View shows a square frame with dimensions 46 IN. by 46 IN. The frame width is 0.98 IN. The test cell is located in the center, with dimensions 3.93 IN. by 3.93 IN. The test cell is made of low-iron glass, RTV 815, and a bare surface. The edge view shows the test cell with dimensions 0.121 IN. by 0.026 IN. by 0.016 IN. The direction of applied force is indicated by an arrow pointing down.

Diagram illustrating the laboratory apparatus for measuring the weight of a plastic sheet. The setup includes a plastic sheet held by a surplus trash container, a module, a dial indicator, a load cell, a transducer, a strain gage, a selector switch, a resistor, a strain indicator, and an X-Y plotter. The plastic sheet is submerged in water. The transducer is connected to the load cell, which is connected to the dial indicator. The strain gage is connected to the selector switch, which is connected to the strain indicator and the X-Y plotter.

Structural Deflection Test Results

LOAD-BEARING MEMBER DEFLECTION AND STRESS

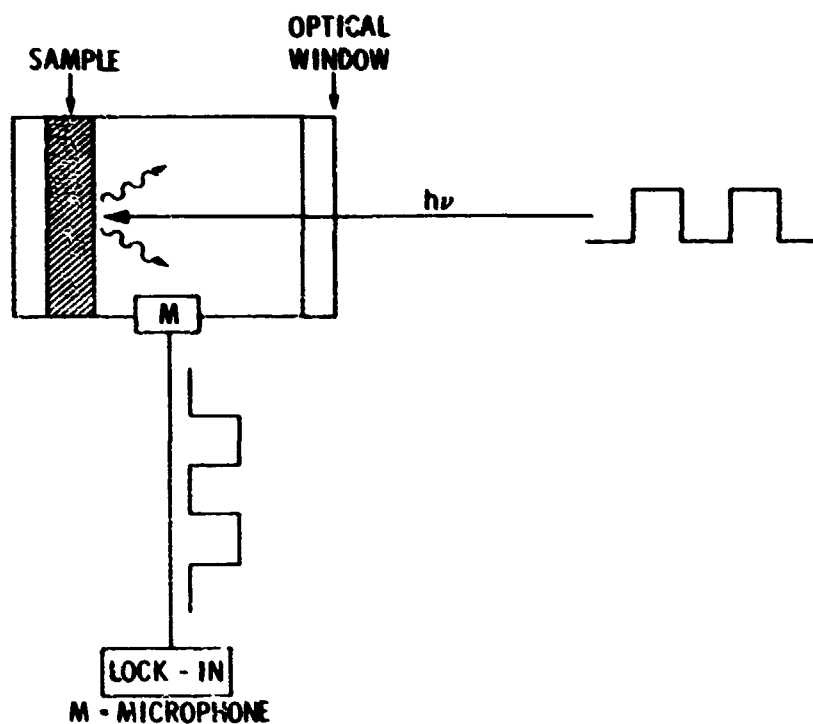
TEST MODULE	DESCRIPTION	DEFLECTION, INCHES		STRESS, PSI	
		TEST	ANALYSIS	TEST	ANALYSIS
SDM -1	GLASS SUPERSTRATE	0.615	0.67	3216	5381
2	GLASS SUPERSTRATE	0.62	0.65	4571	4946
3	GLASS SUPERSTRATE	0.61	0.67	2571	5100
4	GLASS SUPERSTRATE	0.58	0.65	2749	4236
5	PLAIN WOOD SUBSTRATE	1.42	1.33	817	752
6	PLAIN WOOD SUBSTRATE	1.36	1.27	766	741
7	RIBBED WOOD SUBSTRATE	FAILURE	-	-	-
8	STEEL SUBSTRATE	0.42	0.5	2357	4395
9	RIBBED WOOD SUBSTRATE	0.37	0.36	NA	NA

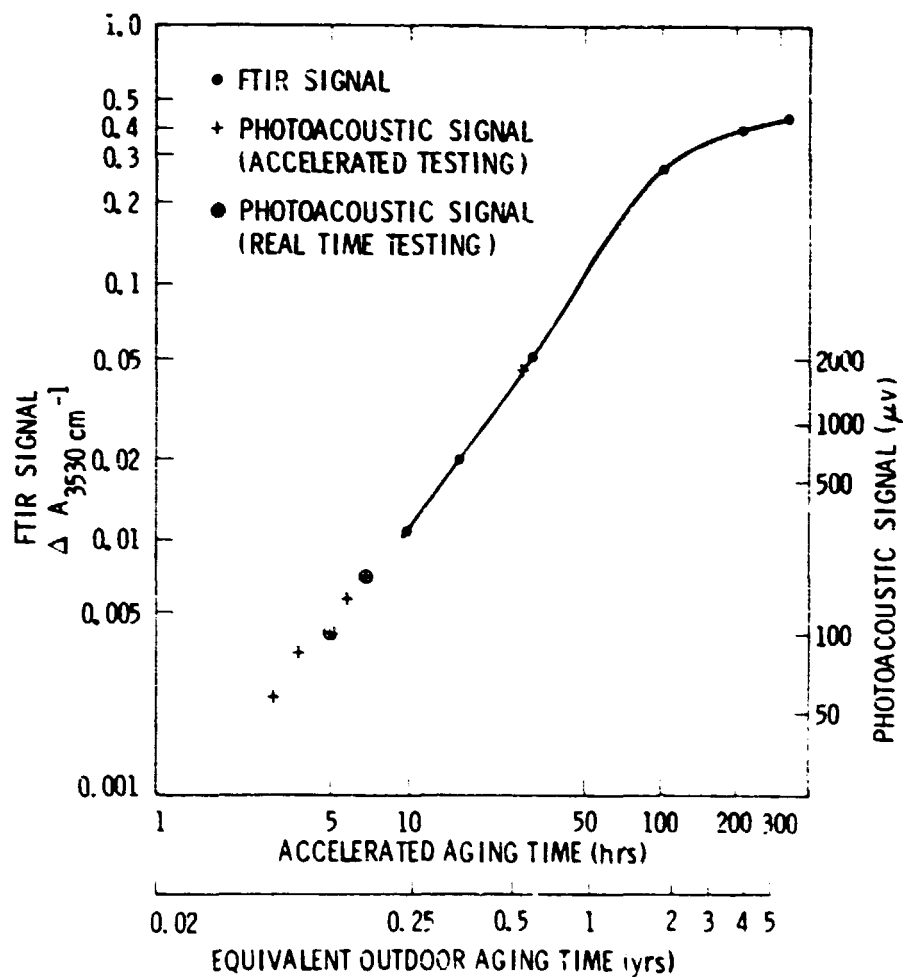
PHOTOACOUSTIC TECHNIQUE

JET PROPULSION LABORATORY

R.H. Liang

Photoacoustic Setup



Formation of (OH) as a Function
of Accelerated and Real-Time Aging

MINIMODULE ENCAPSULANT FIELD TESTING

JET PROPULSION LABORATORY

P. Frickland

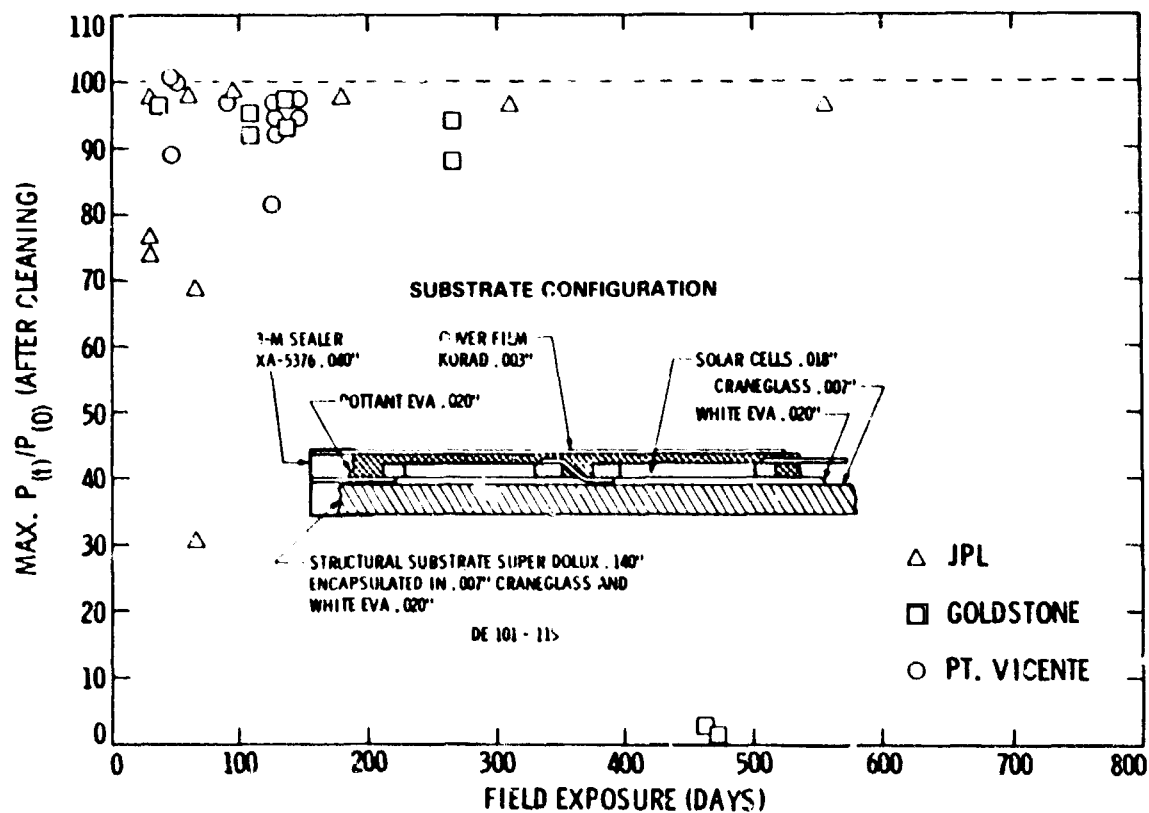
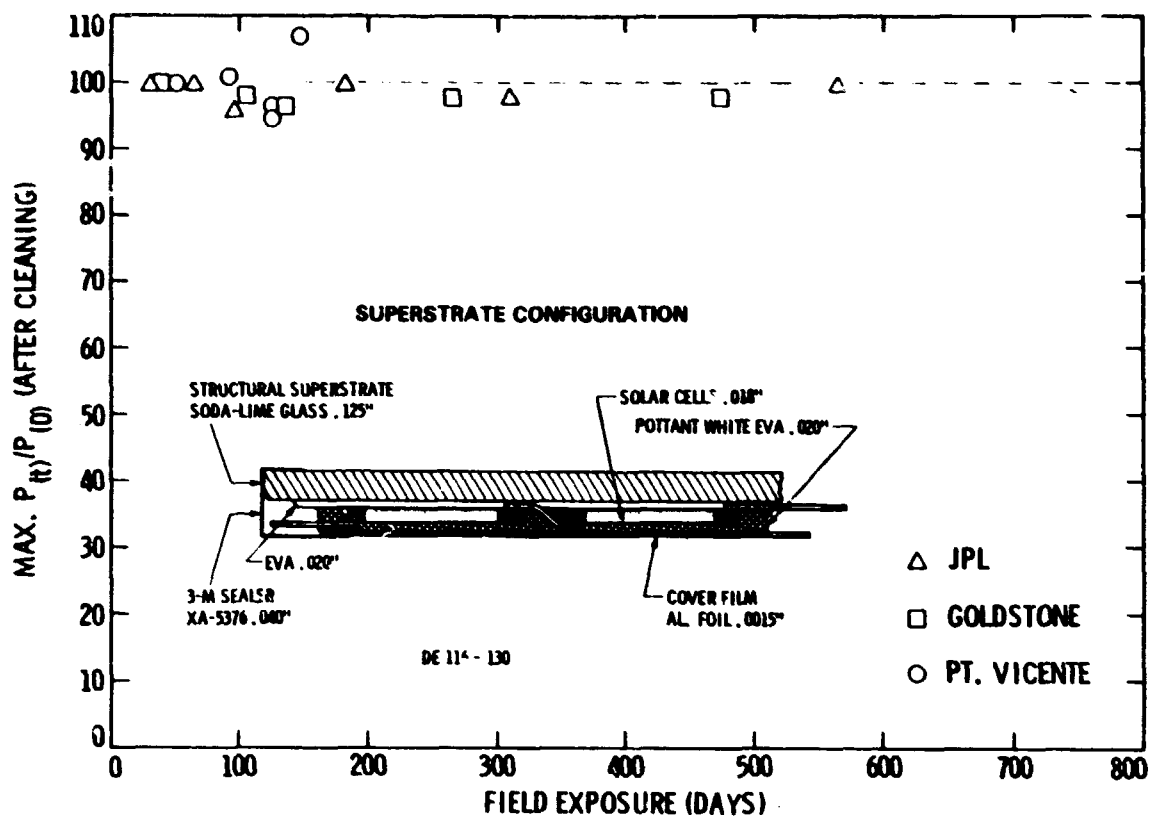
Summary of Minimodule Temperature and
Humidity-Freeze Testing

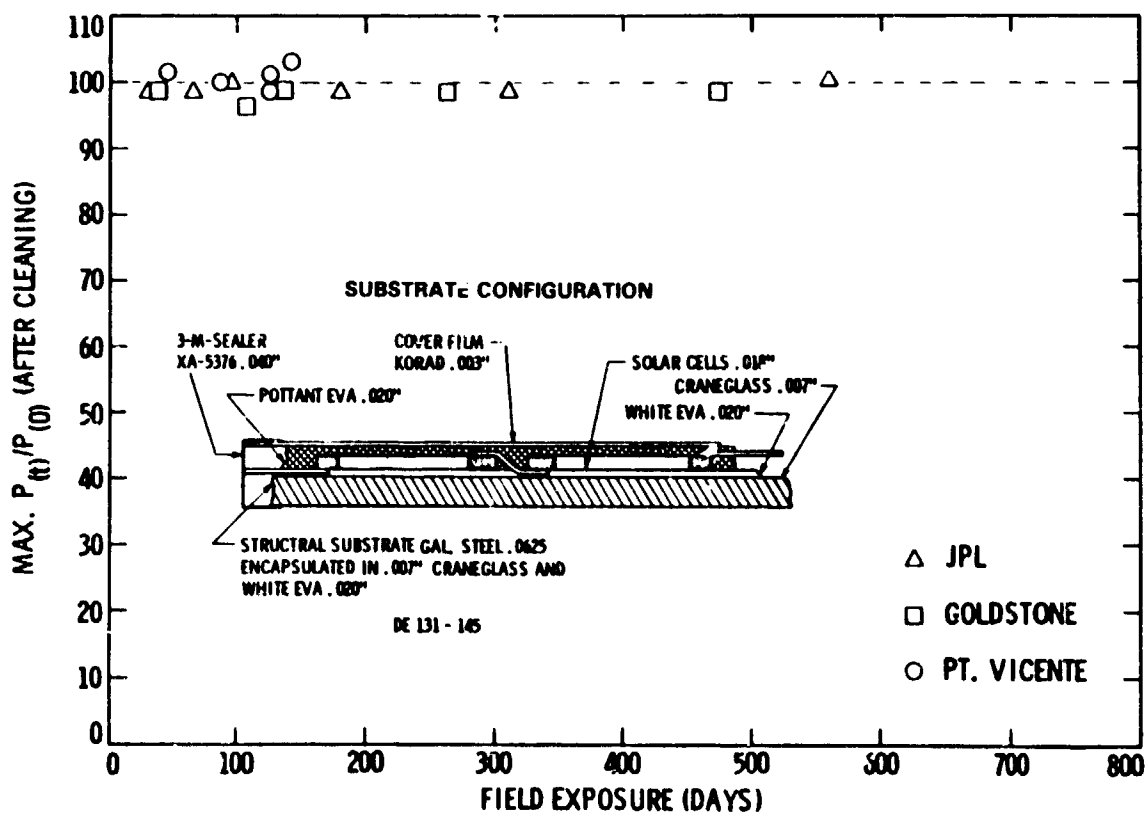
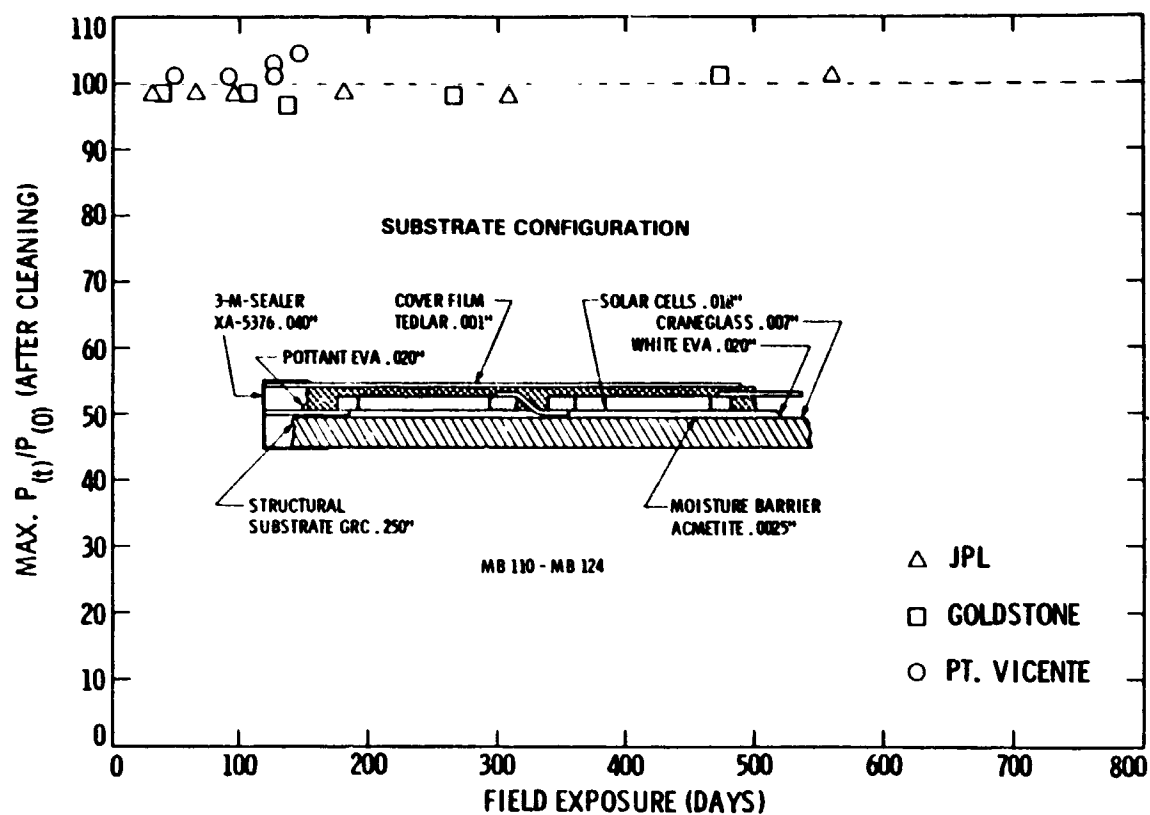
<u>SUBSTRATE</u>	$\Delta P(T)/P(O) \%$	
	<u>TEMP</u>	<u>HUMID/FREEZE</u>
KORAD/EVA/GALVANIZED STEEL (DE 131-145)	- 4	- 6
TEDLAR/EVA/GLASS REINFORCED CONCRETE (MB 110-124)	- 0	-11
KORAD/EVA/SUPER DORLUX (DE 101-115)	-25	-59
<u>SUPERSTRATE (GLASS)</u>		
SODA-LIME GLASS/POLYURETHANE (PW 101-115)	+ 5	+ 1
SODA-LIME GLASS/POLYURETHANE/ACMETITE (PW 116-130)	+ 2	+ 1
SODA-LIME GLASS/EVA/WHITE EVA/CRANGLASS/AL FOIL (DE 116-130)	- 4	- 6
SUNADEX GLASS/EVA/ACMETITE (CE 131-145)	+ 2	+ 1
SUNADEX GLASS/EVA/CRANGLASS/ACMETITE (CE 116-130)	- 2	- 1
SUNADEX GLASS/EVA/CRANGLASS/MYLAR (CE 101-115)	- 2	- 2
SUNADEX GLASS/RTV SILICONE/CRANGLASS/ACMETITE (GE 101-105)	+ 1	+ 2
7070 BOROSILICATE GLASS (ESB)/EVA/ACMETITE (SE 101-110)	+ 1	0, -100

Summary of Minimodule Hail Testing

<u>SUBSTRATE</u>	<u>RESULTS</u>
KORAD/EVA/GALVANIZED STEEL (DE 131-145)	OK
TEDLAR/EVA/GLASS REINFORCED CONCRETE (MB 110-124)	OK
KORAD/EVA/SUPER DORLUX (DE 101-115)	OK
<u>SUPERSTRATE (GLASS)</u>	
SODA-LIME GLASS/POLYURETHANE (PW 101-115)	OK
SODA-LIME GLASS/POLYURETHANE/ACMETITE (PW 116-130)	OK
SODA-LIME GLASS/EVA/WHITE EVA/CRANEGLASS/AL FOIL (DE 116-130)	OK
SUNADEX GLASS/EVA/ACMETITE (CE 131-145)	OK
SUNADEX GLASS/EVA/CRANEGLASS/ACMETITE (CE 116-130)	•
SUNADEX GLASS/EVA/CRANEGLASS/MYLAR (CE 101-115)	OK
SUNADEX GLASS/RTV SILICONE/CRANEGLASS/ACMETITE (GE 101-105)	OK
7070 BOROSILICATE GLASS (ESB)/EVA/ACMETITE (SE 101-110)	BAD (4 @ 25 MPH)

-
- CRACKED AT EDGE ONLY, 3RD IMPACT 52 MPH





CELL AND MODULE FORMATION RESEARCH AREA

D.B. Bickler, Chairman

The Cell and Module Formation Research Area technology session opened with a presentation by Spectrolab, Inc., on its new metallization contract. Work is just beginning on this contract; the presentation was an outline of the program, with test-flow and work-flow diagrams.

Bernd Ross Associates announced that they have noted that the firing of base-metal pastes in reducing atmospheres is dramatically influenced by hydrogen. Apparently the surface of the silicon becomes hydrogenated and does not react with the metal. Carbon monoxide has been found to give excellent results as a reducing atmosphere that will not hydrogenate the silicon surface. Silver fluoride continues to be the leading fluxing agent for glass-free silver-metal systems. The hygroscopic nature of AgF presents a problem; packaging methods are important. Recently fabricated experimental cells have again shown that copper-metal pastes containing AgF make satisfactory back metallizations on silicon cells. This system works well on aluminum-back-surface field cells as well. Insufficient firing temperatures have been shown to result in an anomalous S-shaped I-V curve. This curve characteristic has been modeled satisfactorily using a second diode at the insufficiently fired surface.

Ron Daniel of the JPL FSA Analysis and Integration Area presented a method for optimization of metallization patterns. Individual contributions to cell power losses are considered, as are diffused-layer sheet resistance, metal-to-silicon contact resistance, grid-line conductive loss, bus-bar conductive loss, and metal shadowing of active cell area. An optimization can also include metallization area costs.

Photowatt reported on the status of its development of a process sequence involving an AR coating and thick-film metallization system capable of penetrating the AR coating during firing. The sequence produces solar cells with excessive series resistance. Efforts to build up the metallization using electrolytic copper plating have resulted in chemical attack upon the fired-metal-to-silicon interface. Photowatt has reorganized this effort and is investigating new formulations of thick-film metal pastes that were inspired by developments by other contractors in the Process Development effort of FSA.

Spire Corp. has completed the design of the NMA implantation machine to a point where construction is under way and is scheduled for completion in September 1982. The design incorporates a defocusing and steering device to spread the ion beam and make it more uniform. This technology is attributable to JPL leadership. It has potential usefulness to the semiconductor industry as well as to the photovoltaic industry.

JPL in-house NMA activity has been dealing with implanted back-surface fields and with NMA primary (front) junctions. The effect of thermal pretreatment was also investigated. Experimental cells previously fabricated did not produce open-circuit voltages (V_{oc}) as high as those of cells

CELL AND MODULE FORMATION RESEARCH AREA

processed conventionally. Among the possible causes was that metallic contamination was being introduced into the ion beam from the NMA source. Graphite parts were fabricated to eliminate this possibility, but the performance was not affected. Further experimentation has led to the opinion that implanted back-surface fields are not heavy enough under present methods. New work is starting in an effort to apply NASA pulse-thruster technology to the development of a pulsed-plasma epitaxy machine. This concept has possibilities far beyond silicon back-surface fields, and encompasses advanced semiconductor materials as well.

Solarex presented the last of its work under the MEPSDU (Module Experimental Process Development Unit) contract. It has recently completed the development of three processes: the use of glass beads in a sand-blasting type of process to remove the oxides that remain after firing the aluminum into the silicon back surface; the use of a commercial wave-soldering device to solder-coat the front cell nickel-plated contacts (unsuccessful in coating both sides of the cell), and the use of ion milling (heavy-duty plasma etching) to clean up the n-on-p junction edges of cells that are stacked tightly on top of one another when loaded into the chamber. Solarex performed a cost analysis, using the IPEG methodology, to determine that the current MEPSDU process sequence results in \$0.56 per watt add-on cost up to but not including cell assembly into modules. The new contractual thrust is toward specific processing characteristics unique to polycrystalline silicon. Semix material processing will be emphasized but the other types of polycrystalline material will also be tested (if not by Solarex, by JPL).

Westinghouse also presented the last of its MEPSDU work (that contract was also revised drastically in this reporting period). The Westinghouse effort involved processing through the module fabrication and environmental testing of its design. The previously reported passing of environmental tests at Westinghouse was repeated at JPL; the Westinghouse design more than passed the tests. The cost calculations have a direct inverse relationship to module operating efficiency; the Westinghouse goals include a 12% efficient module. Over the last year the efficiency of Westinghouse panels has increased from 7.5% to 11.2%; it is believed that Westinghouse would have achieved its 12% goal if the contract had not been redirected. The new contract activity focuses upon the junction formation process; the company is developing lower-cost diffusion sources based upon liquid application rather than the present gaseous sources. Ion implantation is also being pursued as a particularly applicable process for dendritic web silicon.

The University of Pennsylvania has completed assessment of metallization patterns by mathematical optimization. Prior work was limited to rectangular geometries. At the end of the assessment, the Westinghouse fan-shaped geometry was analyzed and found to be capable of the same optimization as rectangular geometries. The next assessment activity was directed toward determining the adequacy of currently accepted minority-carrier-lifetime measurement techniques and what, if any, errors are responsible for confusion in cell mathematical modeling activities. Apparently there is sufficient confusion in the accepted literature to cast doubts upon present ability to model advanced photovoltaic structures.

CELL AND MODULE FORMATION RESEARCH AREA

THICK-FILM METALLIZATION

BERND ROSS ASSOCIATES

Bernd Ross

Progress

1. SINCE HYDROGENATED SILICON SURFACES TEND TO REJECT METAL COATINGS, AN ALTERNATIVE REDUCING AMBIENT WAS SOUGHT.
2. PREVIOUSLY FABRICATED PASTES AS WELL AS NEW FORMULATIONS WERE FIRED IN NITROGEN AND CARBON MONOXIDE GASES.
3. SEM ANALYSIS SHOWED EXCELLENT STRUCTURE FOR CO FIRED COPPER ELECTRODES.
4. ELECTRICAL CHARACTERIZATION GAVE GOOD RESULTS FOR CONTACT RESISTANCE STUDIES AS WELL AS SOLAR CELL PERFORMANCE (BACK CONTACTS ONLY).
5. EXPERIMENTS WITH SILVER FLUORIDE CONTAINING DIFFERENT AMOUNTS OF MOISTURE WERE PERFORMED.
6. A SILVER FLUORIDE ACTIVATED COPPER PASTE ELECTRODE WAS OBSERVED TO PENETRATE A 700^Å SILICON NITRIDE LAYER.

Silver Fluoride Experiment

SILVER FLUORIDE FROM TWO SOURCES WAS UTILIZED.

TYPE "H" SILVER FLUORIDE, PACKED IN A PLASTIC BOTTLE APPEARED QUITE WET, WITH VISIBLE LIQUID MOISTURE IN EVIDENCE.

MELTING OCCURRED AT APPROXIMATELY 300°C (MELTING POINT FOR DRY MATERIAL APPROXIMATELY 435°C) FOR "H" MATERIAL, ACCOMPANIED BY BUBBLING AND AFTER REACTION TO METALLIC SILVER A GLASSY RESIDUE WAS IN EVIDENCE.

TYPE "A" SILVER FLUORIDE, PACKED IN A PLASTIC BAG WITHIN A GLASS JAR, SHOWED CONSIDERABLY LESS MOISTURE, HOWEVER, GRAIN AGGLOMERATION INDICATED A MOISTURE PROBLEM STILL EXISTS.

TYPE "A" MATERIAL MELTED CLOSER TO THE PUBLISHED MELTING POINT, AND NO MACROSCOPIC AMOUNTS OF RESIDUE WERE SEEN.

SEM MICROGRAPHY SHOWED EVIDENCE OF THE EXISTENCE OF SMALL AMOUNTS OF GLASSY MATERIAL FOR TYPE A SILVER FLUORIDE ALSO.

Solar-Cell Experiment

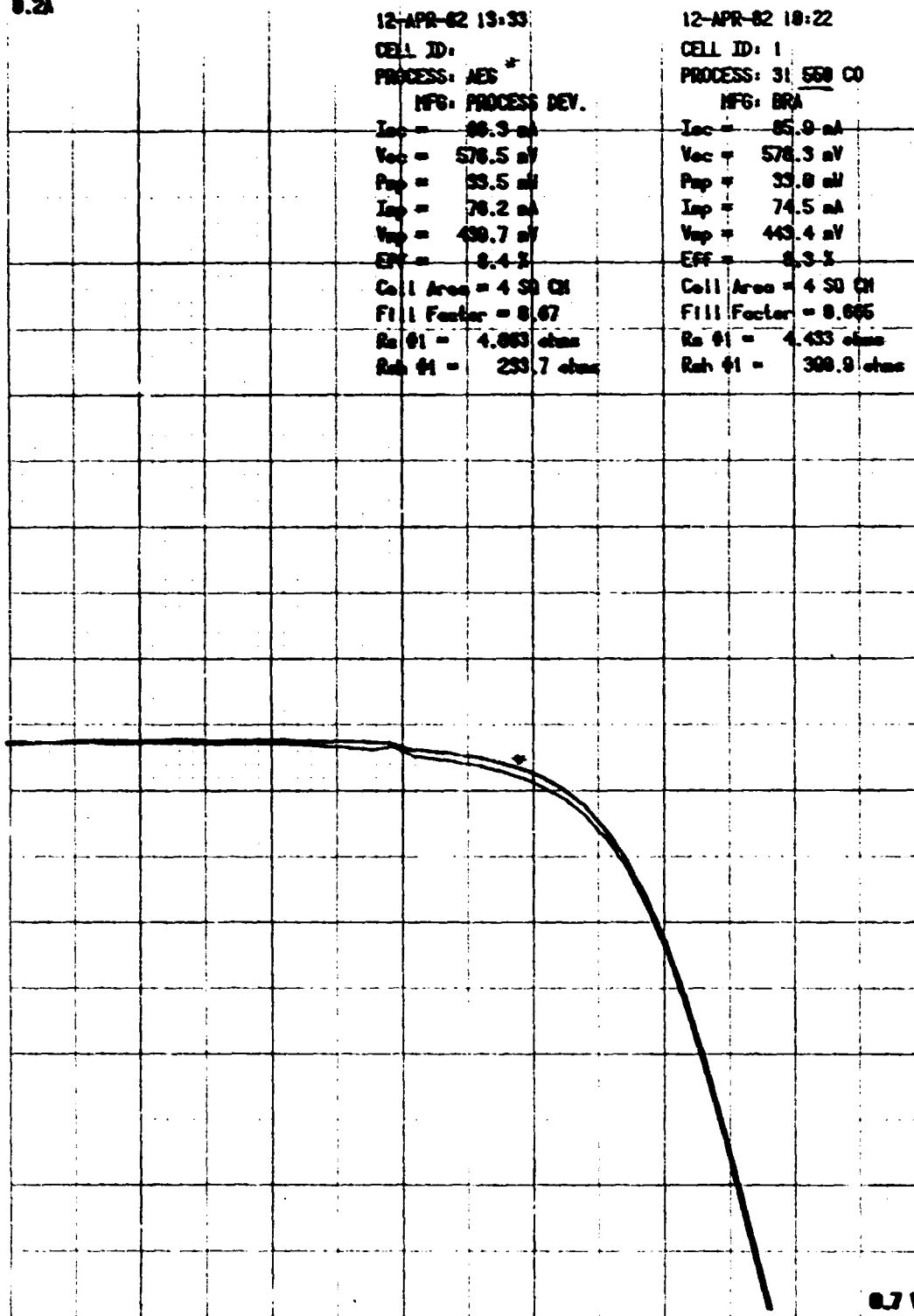
F31 COPPER PASTE WITH 0.1 WT % AgF, 10 WT % Pb
AND 0 WT % AL-Si EUTECTIC

F32 COPPER PASTE WITH 0.1 WT % AgF, 10% Pb AND
5 WT % AL-Si EUTECTIC

PASTE	FIRING TEMPERATURES(°C)	QTY	AMBIENT GAS	AVERAGE UNCOATED EFFICIENCY AM %	AVERAGE FILL FACTOR
F31	550	3	N ₂	5.9	0.476
F31	550	3	CO	7.7	0.637
F31	600	3	CO	6.5	0.551
F31	650	3	CO	8.1	0.676
F32	550	3	CO	7.1	0.660
F32	600	3	CO	8.0	0.722
F32	650	3	CO	7.5	0.739

C-5

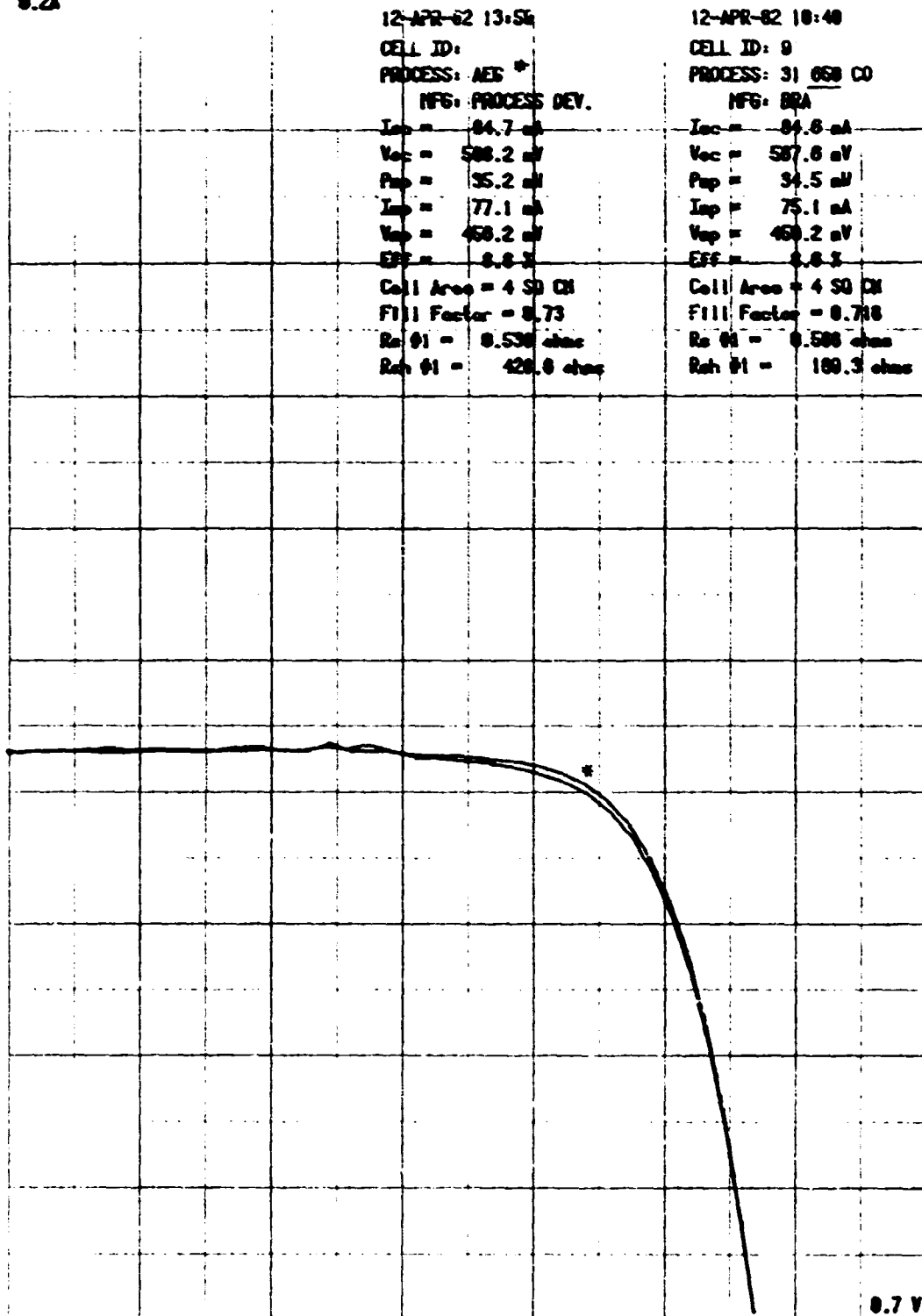
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CELL AND MODULE FORMATION RESEARCH AREA

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CELL AND MODULE FORMATION RESEARCH AREA

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12-APR-82 14:28

CELL ID:

PROCESS: AES #

MFG: PROCESS DEV.

Isc = 81.7 mA

Voc = 572.8 mV

Pmp = 34.4 mW

Imp = 75.4 mA

Vmp = 457.8 mV

EFF = 8.6%

Cell Area = 4.50 CM

Fill Factor = 8.737

R_s ϕ 1 = 8.525 ohms

R_{sh} ϕ 1 = 238.2 ohms

12-APR-82 18:59

CELL ID: 17

PROCESS: 32 688 C0

MFG: BRA

Isc = 81.2 mA

Voc = 571.1 mV

Pmp = 33.7 mW

Imp = 73.5 mA

Vmp = 458.4 mV

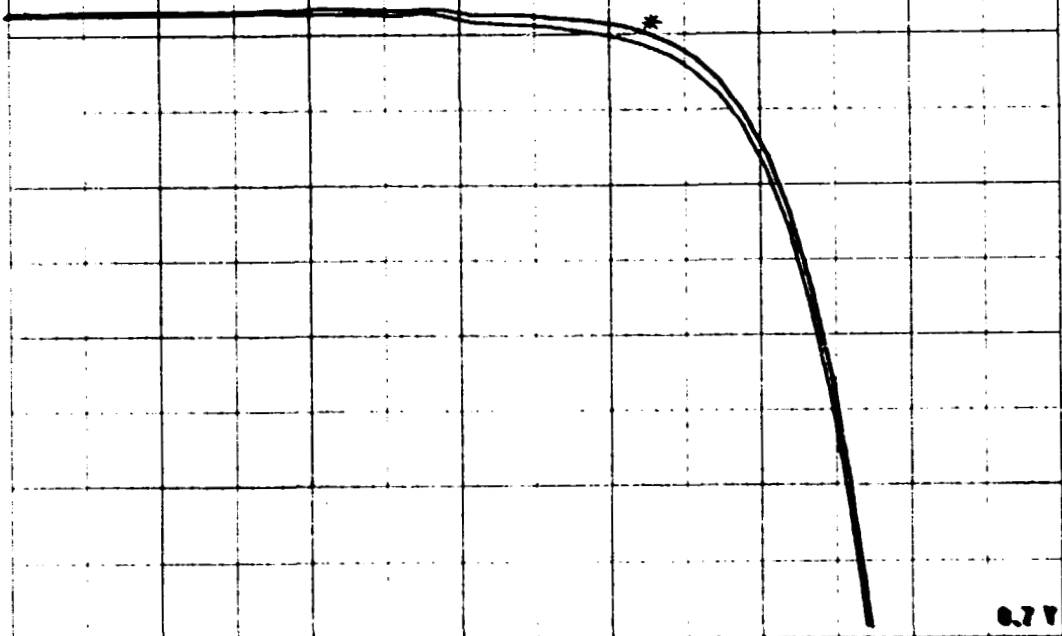
EFF = 8.4%

Cell Area = 4.50 CM

Fill Factor = 8.728

R_s ϕ 1 = 8.587 ohms

R_{sh} ϕ 1 = 249.8 ohms



0.20

12-APR-82 13:46

CELL ID:

PROCESS: AES #

MFG: PROCESS DEV.

Is_c = 86.3 mAV_{oc} = 554.8 mVP_{mp} = 18.2 mWI_{mp} = 88.6 mAV_{mp} = 200.4 mV

EFF = 4.5 %

Cell Area = 4 SQ CM

Fill Factor = 8.378

R_s ϕ 1 = 8.182 ohmsR_{sh} ϕ 1 = 89.5 ohms

12-APR-82 16:28

CELL ID: 3

PROCESS: 38 568 N2

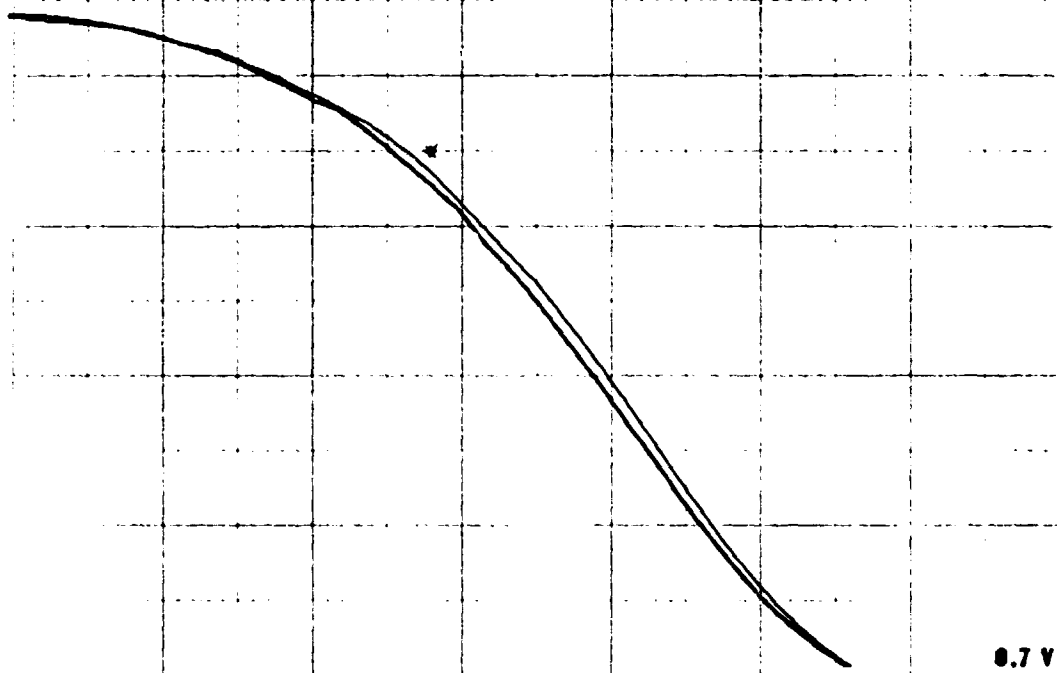
MFG: BRA

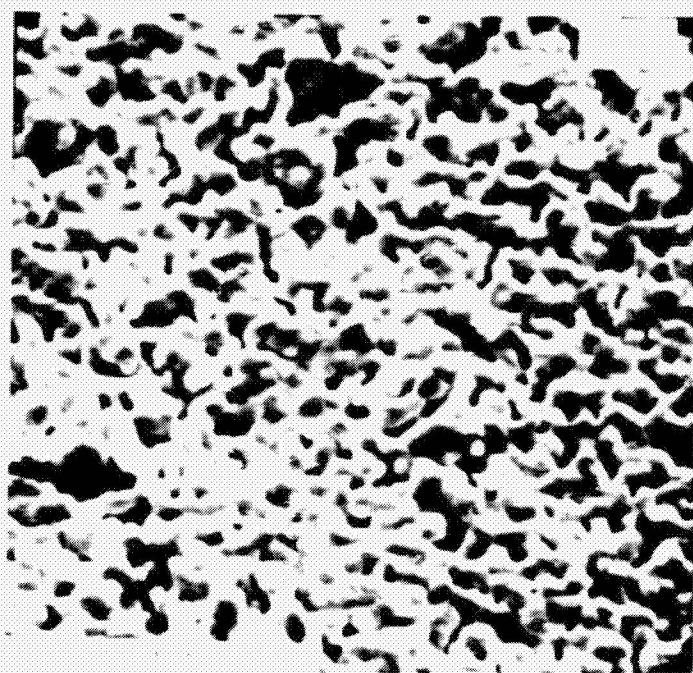
Is_c = 86.4 mAV_{oc} = 557.1 mVP_{mp} = 18.6 mWI_{mp} = 84.7 mAV_{mp} = 207.6 mV

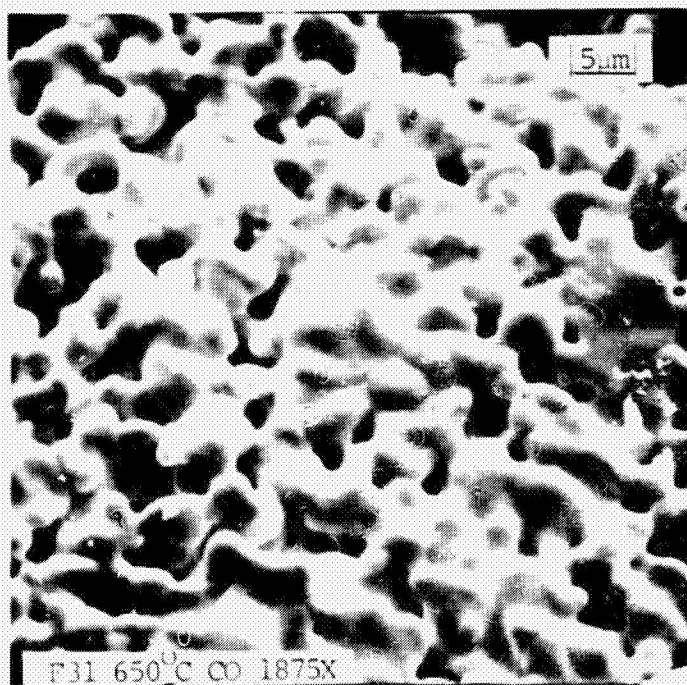
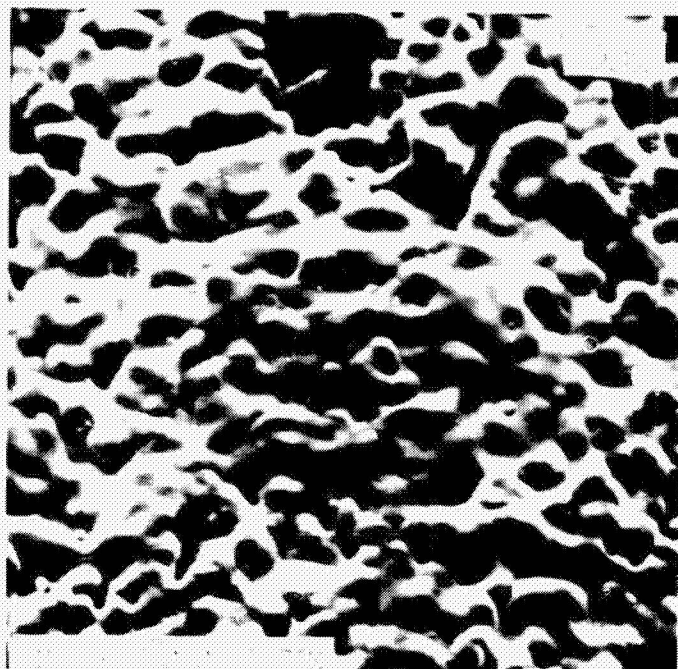
EFF = 4.7 %

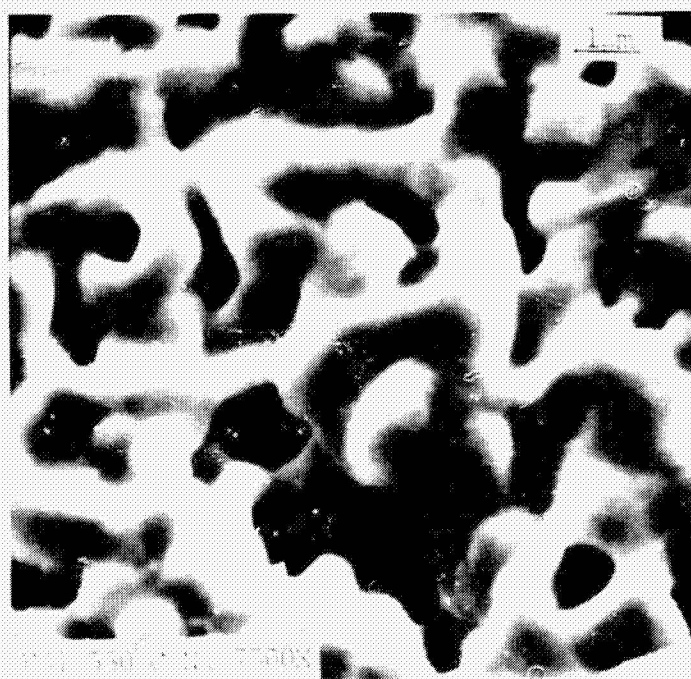
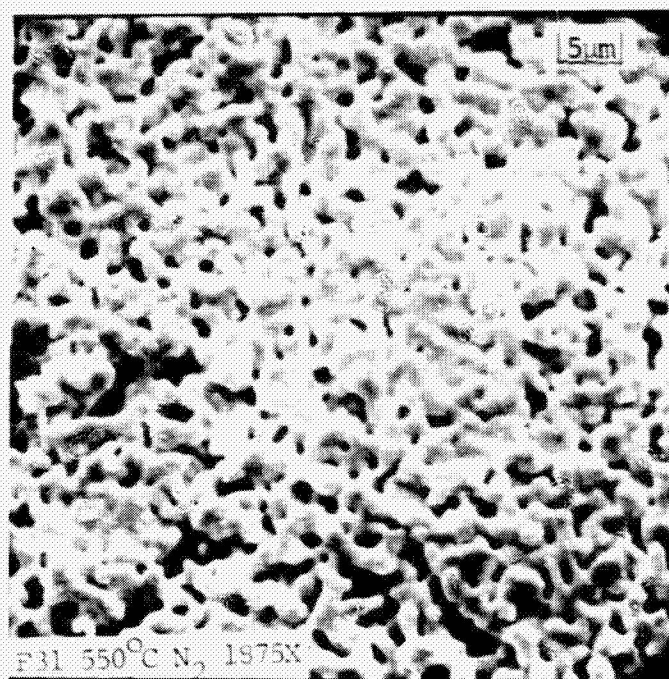
Cell Area = 4 SQ CM

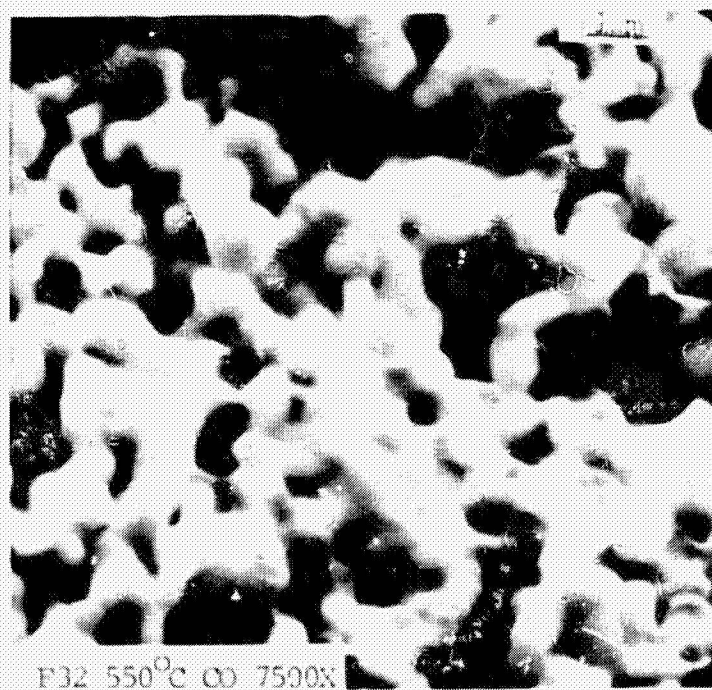
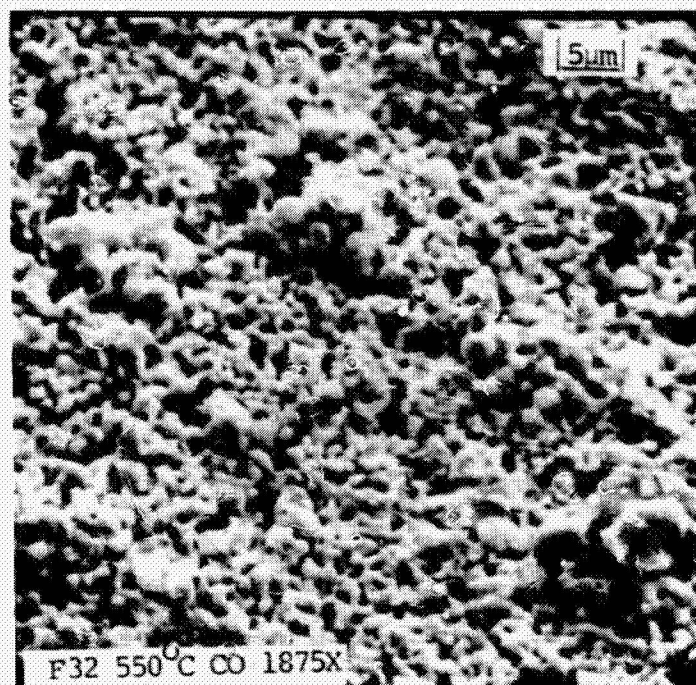
Fill Factor = 8.386

R_s ϕ 1 = 8.988 ohmsR_{sh} ϕ 1 = 76.8 ohms









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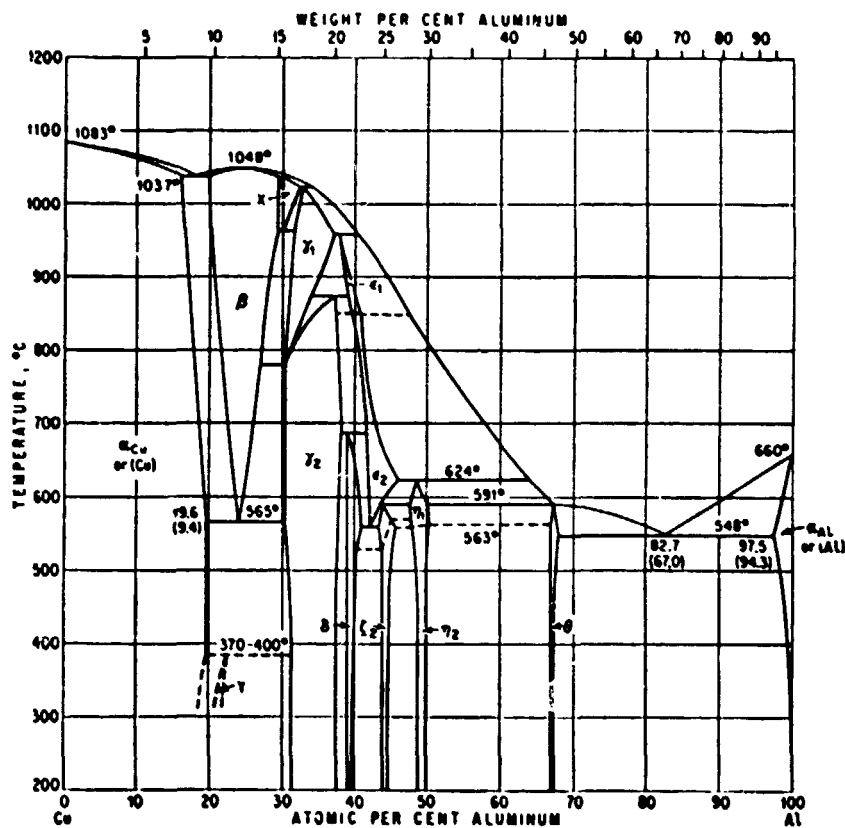
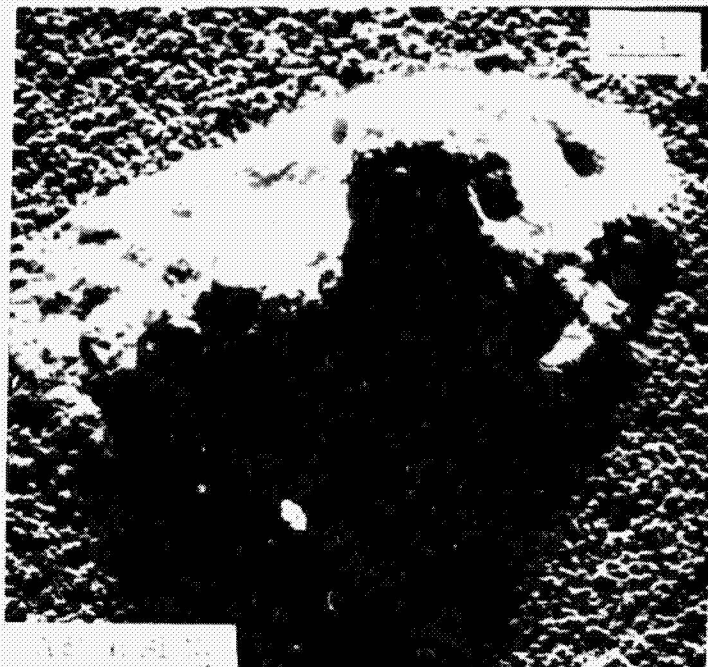


Fig. 52. Al-Cu. (See also Fig. 53.)

Phase Diagram of Al-Cu
System, from "Constitu-
tion of Binary Alloys" by
M.Hansen, 2nd Ed. p.85
Mc Graw Hill, New York '58



CELL AND MODULE FORMATION RESEARCH AREA

Conclusions and Problems

1. CARBON MONOXIDE REDUCING AMBIENTS PROVIDED WELL SINTERED COHERENT COPPER STRUCTURES WITH RELATIVELY LARGE GRAIN AT THE LOWEST TEMPERATURES.
2. ADHERANCE OF CO FIRED COPPER ELECTRODES WAS SIGNIFICANTLY SUPERIOR TO HYDROGEN FIRED SPECIMEN.
3. ELECTRICAL PROPERTIES OF DEVICES AND TEST STRUCTURES ARE SATISFACTORY.
4. ELECTRODE STRUCTURES CONTAINING ALUMINUM RESULTED IN DIS-COLORED APPEARANCE WITH LITTLE OR NO SINTERING AND SMALL GRAINSIZE. ELECTRICAL PROPERTIES, HOWEVER, APPEARED UNAFFECTED.
5. PROCUREMENT AND STORAGE OF SILVER FLUORIDE REQUIRES SPECIAL CARE.

OPTIMIZATION PROGRAM/DESIGN METHOD FOR SOLAR CELL GRID PATTERNS

JET PROPULSION LABORATORY

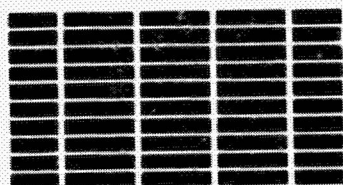
R.E. Daniel

Introduction

- **There Is Extensive Literature About the Series Resistance Losses Associated With the Solar Cell Grid Pattern; However, There Have Been No Reports That Assist the Grid Pattern Designer to Design an Optimal Grid Pattern of Two or More Design Variables**
- **An APL Program Has Been Developed That Uses a Non-Linear Optimization Technique to Find Optimal Design Values for the Grid; the Power Losses Analyzed Include Photoconductor Sheet Losses, Fine Grid and Bus Resistance Losses and Shadow Losses, and Contact Resistance Between the Sheet and the Fine Grid Lines**
- **Typical Design Parameters Might Be:**
 - **Fine Grid Line Width**
 - **Fine Grid Line Spacing**
 - **Bus Bar Width**
 - **Metallization Thickness**
- **Assumptions**
 - **Current Uniformly Generated on the Surface of the Cell**
 - **Power Loss Between the Fine Grid Lines Is Found Using Sectional Integration**
 - **Fine Grid Lines and Bus Bar(s) Are Orthogonal**
 - **Bus Bar Same Thickness as the Fine Grid (or Strapped)**
 - **Fine Grid Line Width and Metallization Thickness at a Predetermined Ratio**

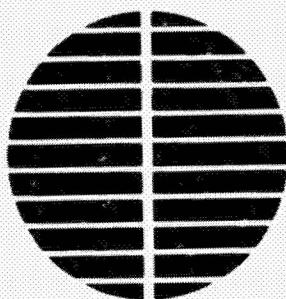
Cell Shape and Grid Geometry

MULTIPLE-BUS RECTANGULAR CELL

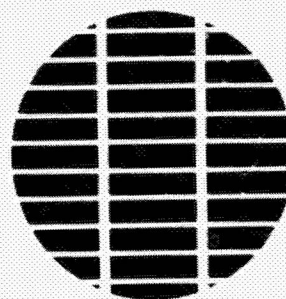


ROUND CELLS

ONE-BUS CELL



TWO-BUS CELL



Power Loss Equations

General Form
of Resistive Losses

$$P = \int I^2 dR$$

Sheet Loss to One Line

$$P_{SH} = 2 \int_0^{s/2} \frac{(J_M I_{xy})^2}{I_x} \rho_s dy$$

Fine Grid One Line

$$P_{FG} = \int_0^{I_x} \frac{(J_M I_x x)^2}{bt} \rho_m dx$$

Bus Bar

$$P_B = 2 \int_0^{I_B} \frac{(J_M I_x y)^2}{W_B t} \rho_m dy$$

Shadow

$$P_{SD} = J_M V_M (\text{Area Bus and Fine Grid})$$

CELL AND MODULE FORMATION RESEARCH AREA

Contact Resistance

$$P_c = I^2 R_c$$

$$R_c = \frac{\rho_c}{\text{Area Fine Grid}} \quad (\text{Inverse Area Relationship})$$

or

$$R_c = \frac{(\rho_s \rho_c s)^{1/2}}{l x^{3/2}} \quad (\text{Current Crowding})$$

where: J_M (mA/cm²) Current Density at Maximum Power

V_M (volts) Voltage at Maximum Power

ρ_m (Ω -cm) Resistivity of Metal

ρ_s (Ω /) Resistivity of Sheet

ρ_c (Ω -cm²) Contact Resistivity

W_B (cm) Width of Bus Bar

s (cm) Spacing Between Fine Lines

b (cm) Width of Fine Lines

t (cm) Metal Thickness

$l x$ (cm) Length of Fine Line

L_B (cm) Length of Bus Bar

Optimization Method

- Procedure Uses the Power-Loss Equations as the Objective Function $P_T = \sum P$ (All Losses)
- Then, the First Partial Derivative of the Function With Respect to the Design Variables is Set Equal to Zero.

$$f_i(X) = \frac{\partial P_T}{\partial \theta_i} = 0 \quad (\theta_i \text{ are the design variables}) \quad i = 1, 2, \dots, n$$

- These Equations Are Solved by a Modified Newton-Raphson Method.

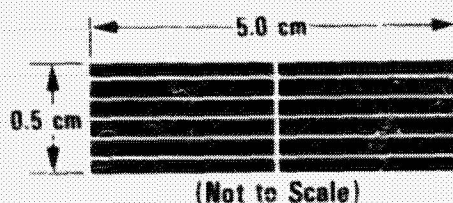
$$f_i(X) = f_i(X^K) + \Delta f_i(X^K) (X - X^K); X^K \text{ is a Given Value}$$

- Matrix Notation

$$A_K + B_K (X - X^K) = 0$$

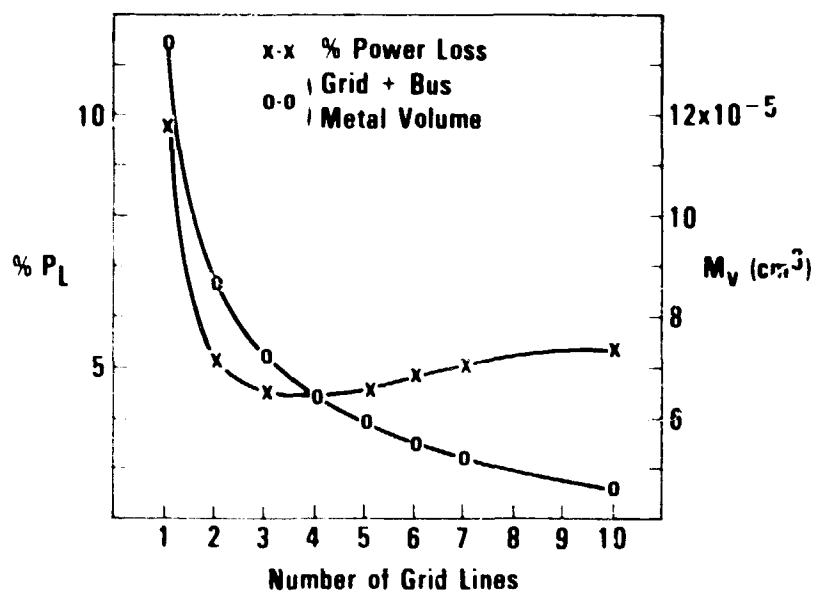
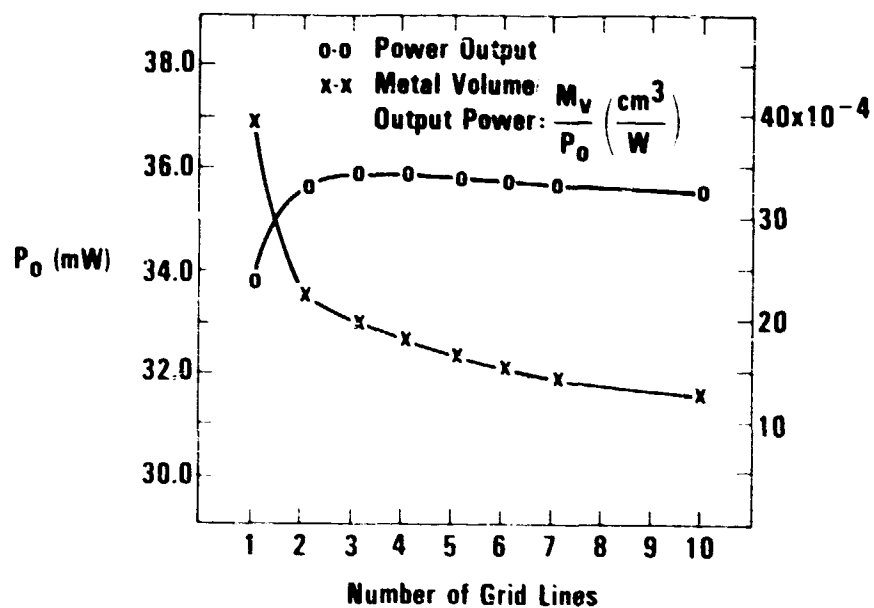
$$X - X^K = B_K^{-1} A_K$$

Rectangular Cell Example

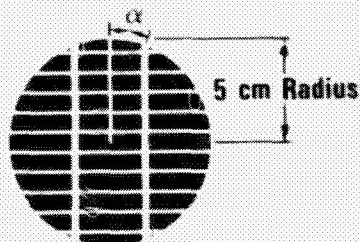


	OPTIMAL DESIGN	4 GRID LINES	10 GRID LINES	INPUT	
P_T , Total Power Lost (mW)	1.68	1.70	2.02	Length	5 cm
% Loss	4.48	4.5	5.4	Width	0.5 cm
A, Fine Grid Spacing (cm)	0.140	0.125	0.050	No. Buses	1
W _B , Bus Bar Width (μ m)	142.0	147.8	202.45	J _M	0.03 A/cm ²
B, Fine Grid Width (μ m)	32.3	29.9	15.90	V _M	0.5 Volts
T, Metal Thickness (μ m)	10.4	9.6	5.1	ρ_M	$1.7 \times 10^{-6} \Omega\text{-cm}$
M _V , Metal Volume (cm) ³	7.6×10^{-5}	6.4×10^{-5}	4.5×10^{-5}	ρ_c	0.001 $\Omega\text{-cm}^2$
				ρ_s	60 Ω
				B:T	3.1

Rectangular Cell: Sensitivity to Number of Grid Lines



Round Cell: 2-Bus Example



	SINGLE METALLIZATION	STRAPPED BUS (50 μ m)	INPUT	
T (mW)	219.3	169.7	Deg. (α)	24
% Loss	20.68	16.00	Radius	5
A (cm)	0.443	0.331	J _M	.03
V _B (cm)	0.184	0.096	V _M	.45
B (μ m)	396.0	218.0	δ m	1.6×10^{-6}
T (μ m)	15.9	8.7	δ B	1.7×10^{-6}
Bus Vol.(cm ³)	5.4×10^{-3}	1.5×10^{-3}	δ c	0.01
Grid Vol.(cm ³)	9.1×10^{-3}	3.7×10^{-3}	δ s	38
			B:T	25

Summary

- The Program Brings Together Two Standard Analyses:
The Power Loss Equations and the Newton-Raphson Technique
- The Result is a Program That Will Provide an Optimal Grid Design, i.e.,
One That Minimizes the Total Power Loss
- Program Can Also Be Used to Do Sensitivity Analysis
- Operation of the Program Is Being Prepared for COSMIC
- Experiments Are Under Way to Verify the Predictive Accuracy of the
Power-Loss Equations
- Program Can Be Extended to Include Other Cell Shapes, Design
Geometries, Cell Characteristics and Rudimentary Cost Sensitivities

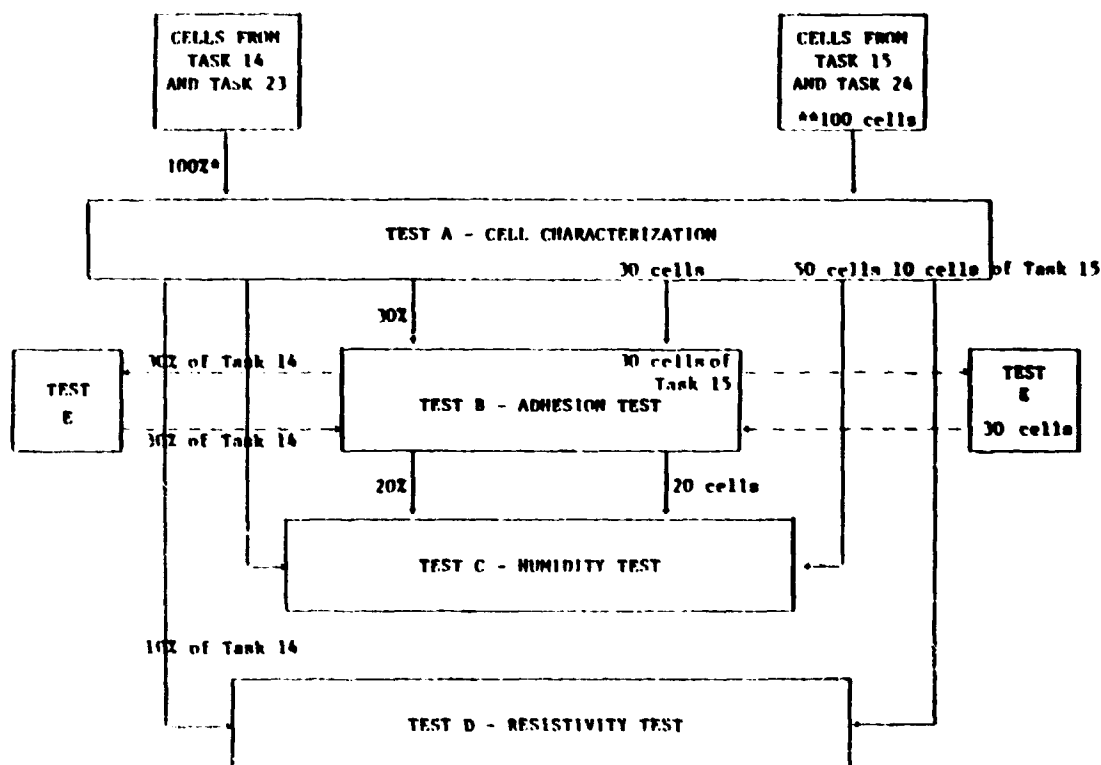
CELL AND MODULE FORMATION RESEARCH AREA

THICK-FILM METALLIZATION

SPECTROLAB, INC.

Mark Gillanders

Test Flow Diagram



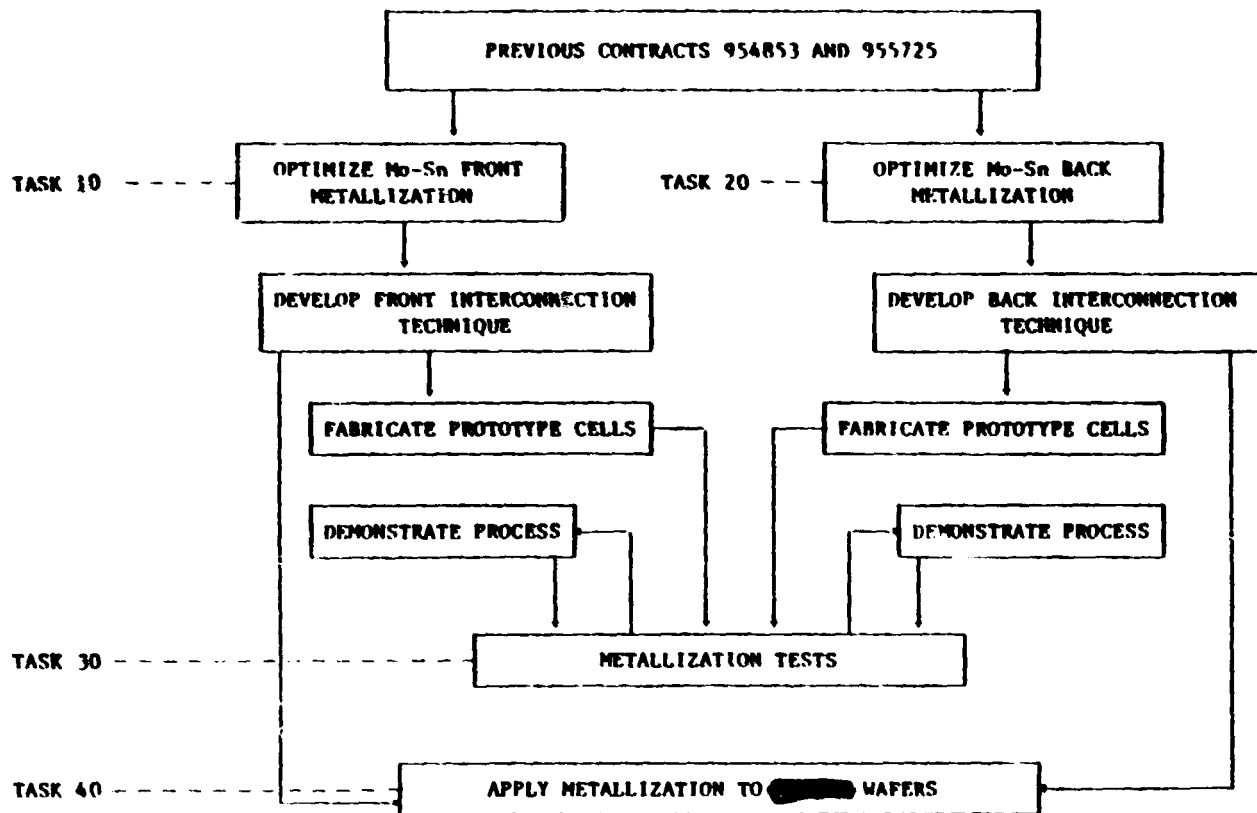
*Note: The percentage indicated from one test area to the next is the percentage of the total cells produced from each of Tanks 14 and 23.

**Note: The number indicated from one test area to the next is the number from each of Tank 15 and 24.

CELL AND MODULE FORMATION RESEARCH AREA

Work Flow Diagram

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NICKEL/COPPER METALLIZATION

PHOTOWATT INTERNATIONAL, INC.

Goals

- TO DEVELOP A RELIABLE METALLIZATION WHICH:
 - USES NICKEL PASTE PRINTED OVER (Si_3N_4) AR COATING
 - WHEN SINTERED PENETRATES THROUGH Si_3N_4 AND BONDS TO SILICON
 - USES BRUSH PLATING OF COPPER FOR ADDITIONAL CONDUCTIVITY
 - PRODUCES 4" DIAMETER CELLS OF EFFICIENCY IN EXCESS OF 10% UNDER AMI 28°C
 - HAS PULL STRENGTH WITH 5 mm WIDE STRAP OF > 2 LBS WHEN PULLED 90° TO SURFACE
- TO PROVIDE COST DATA ON THE ABOVE SYSTEM

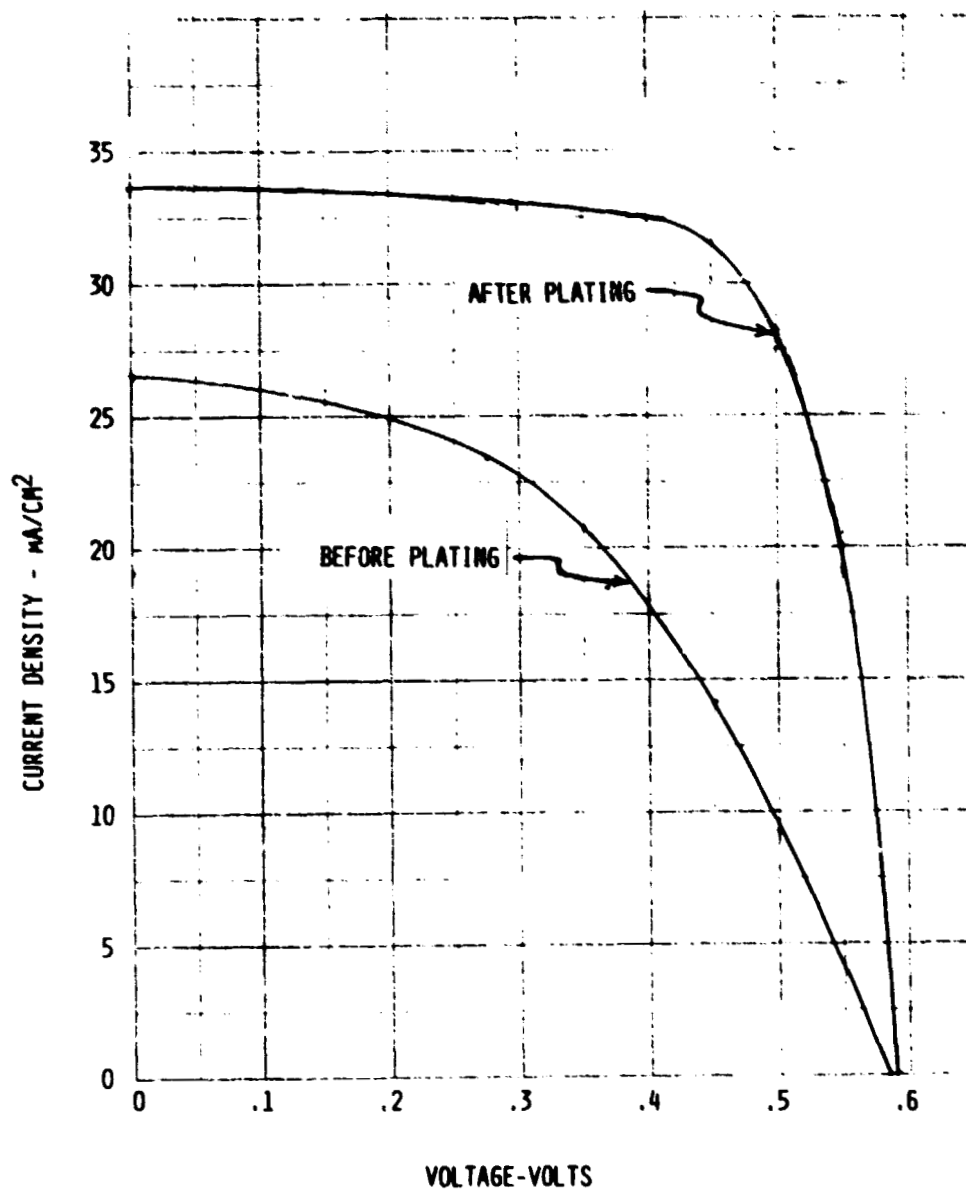
Process Sequence

1. TEXTURE ETCH
2. POCl_3 DIFFUSION
3. BACK ETCH
4. DEPOSIT NITRIDE
5. PRINT & FIRE ALUMINUM BACK
6. PRINT & FIRE NICKEL GRID
7. COPPER PLATE
8. TEST

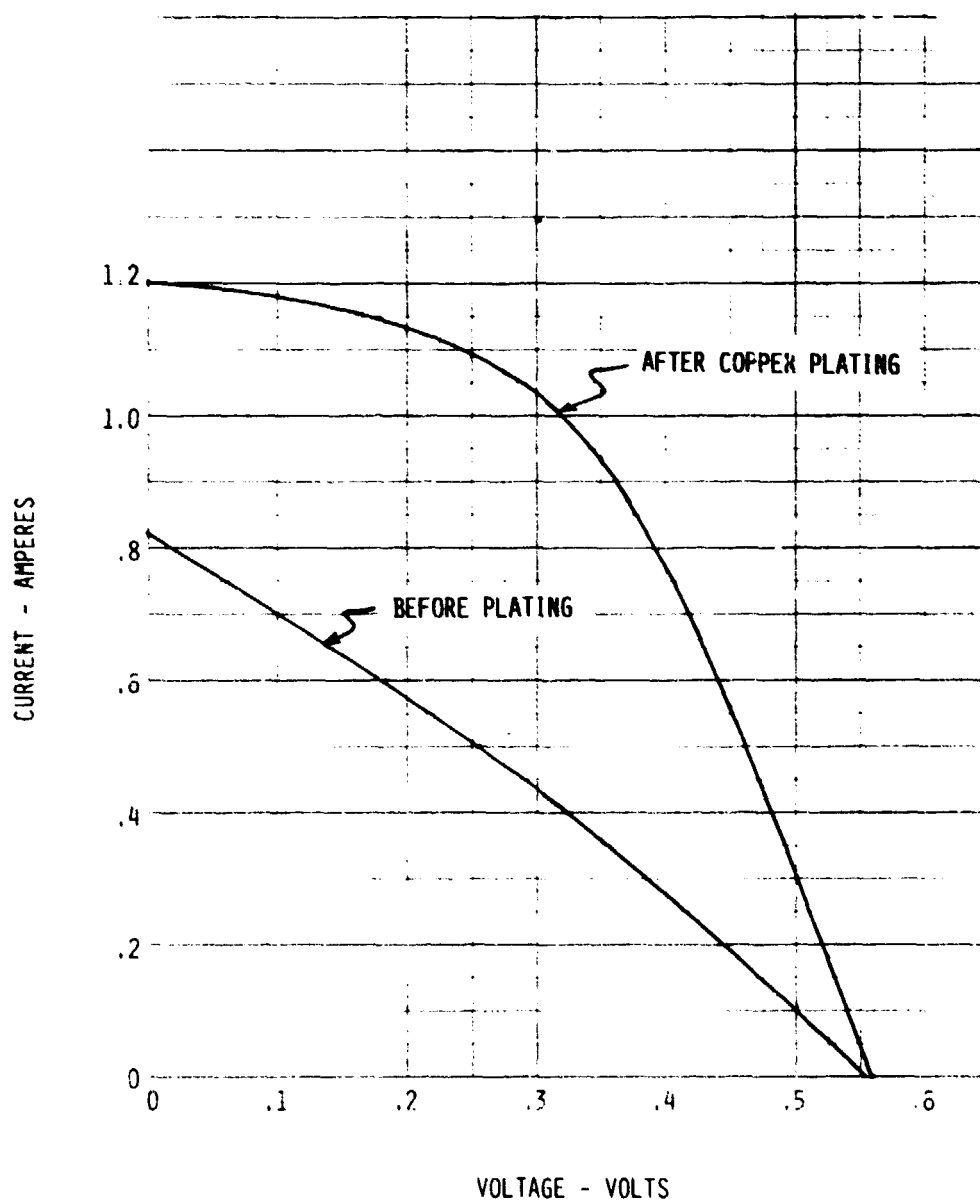
Series Resistance Problem

1. CONTACT RESISTANCE THRU SILICON NITRIDE
 - A. AgF NOT ATTACKING NITRIDE
 - B. AgF DEPLETED BY REACTING WITH FRIT
2. LOSS OF CONTACT BY REACTION WITH PLATING SOLUTION
3. OTHER

TFS #5517 Ni + 30% EMCA #7069 Ag Fired at 700°C for 5 min



ESL Paste E + 5% EMCA Ag 7069 Fired at 700°C for 6 min



CELL AND MODULE FORMATION RESEARCH AREA

Plating

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1. REACTION OF PLATING SOLUTION WITH FRIT
2. POROSITY OF PLATED LAYER

New Directions

- FRITLESS PRINTING INKS
- ADDITIVES TO PENETRATE NITRIDE
 AgPO_3
 NiF_2
- ADDITIVES TO IMPROVE ADHESION
 T_1
 Au .

CELL AND MODULE FORMATION RESEARCH AREA

ION IMPLANTATION AND PULSE ANNEALING

SPIRE CORP.

Program Description

OBJECTIVES

1. To develop junction formation processes using Ion Implantation and pulsed annealing using equipment designed especially for solar cells.

PROGRAM PLAN

1. Develop 4" Capability Pulse Annealer
2. Develop 4" Capability NMA Ion Implanter
3. Use this equipment to develop junctions on Advanced Sheet Materials

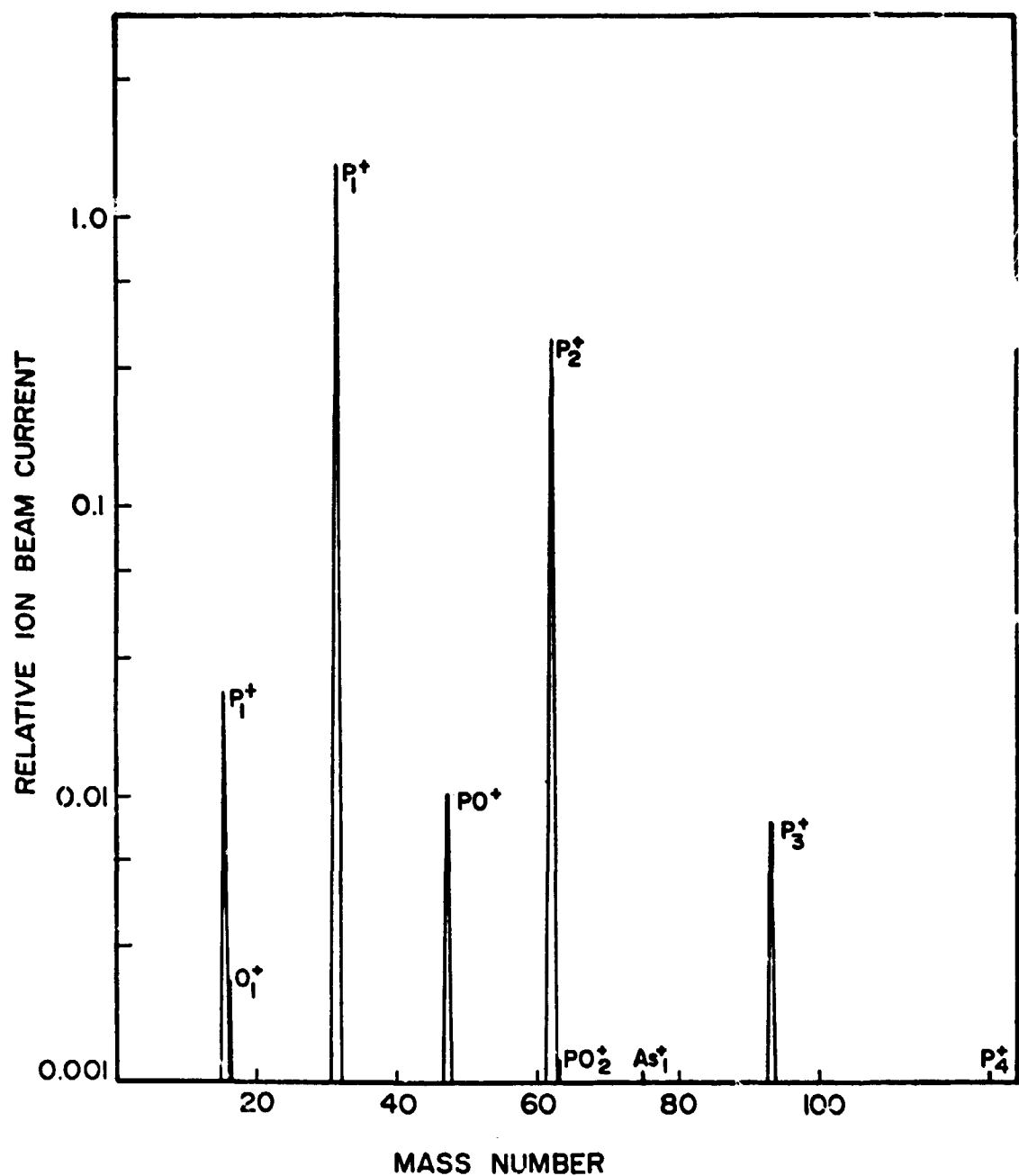
Non-Mass-Analyzed (NMA) Implant Cells (Spire Test Facility)

	Lot 3969 Non Analyzed Implant	Lot 3969 Standard Implant
Voc (mV)	578 \pm 1	573 \pm 1
Jsc (mA/cm ²)*	28.7 \pm 0.16	28.2 \pm 0.08
Fill Factor (%)	75.7 \pm 0.3	76.0 \pm 0.2
η (AMO) (%)	9.29 \pm 0.05	9.08 \pm 0.04
η (AM1) ⁺ - Extrapolated (%)	15.4 \pm 0.08	15.0 \pm 0.07
R _{sheet} (OHMS per square)	61.6 \pm 3.1	55.4 \pm 0.6
ρ (ohm-cm)	10	10

* No A.R. coating

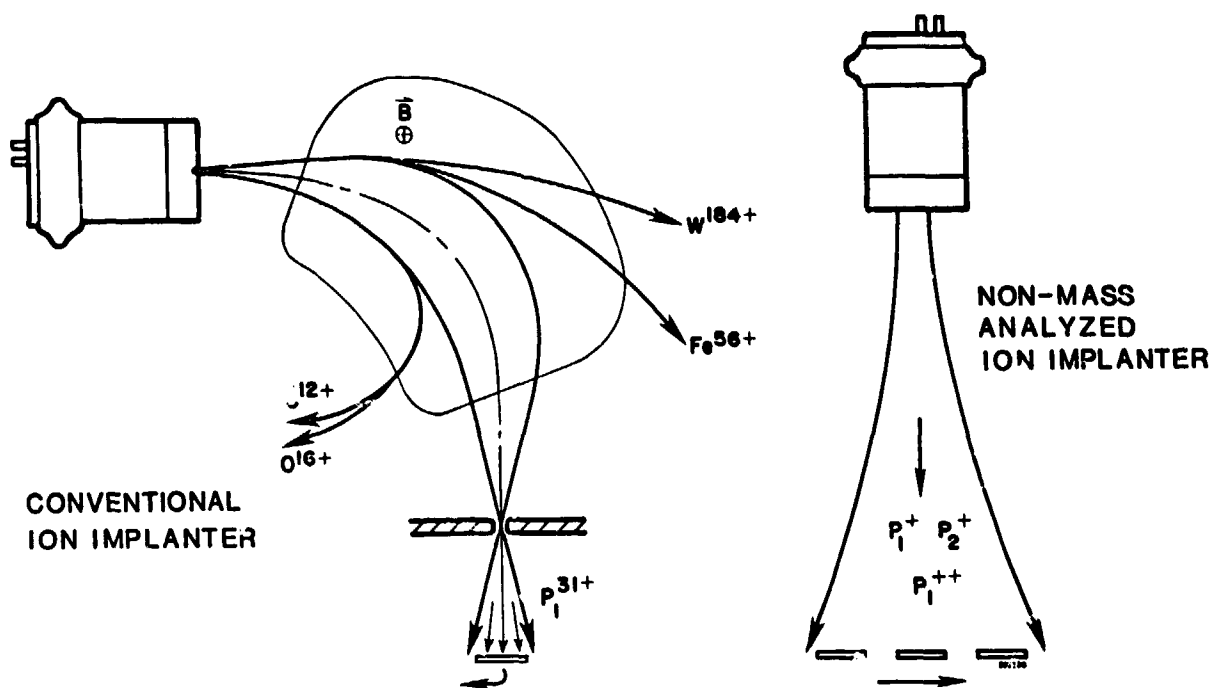
+ Times 1.4 for A.R. coat and times 1.18 for AM1

Ions Produced by Commercial-Grade Solid Phosphorus



CELL AND MODULE FORMATION RESEARCH AREA

Ion Implanter Types



NMA Implanter Advantages

- Simple Machine
- Higher Throughput of Solar Cells
- Easily Automated (Continuous vs. Batch)
- Custom made for Solar Cells

CELL AND MODULE FORMATION RESEARCH AREA

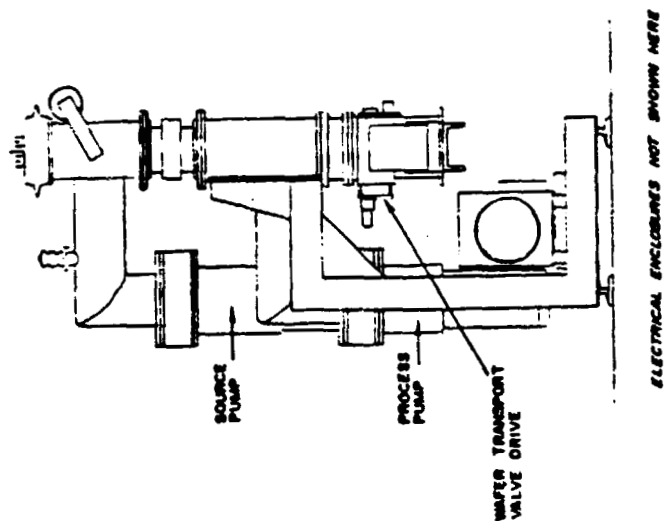
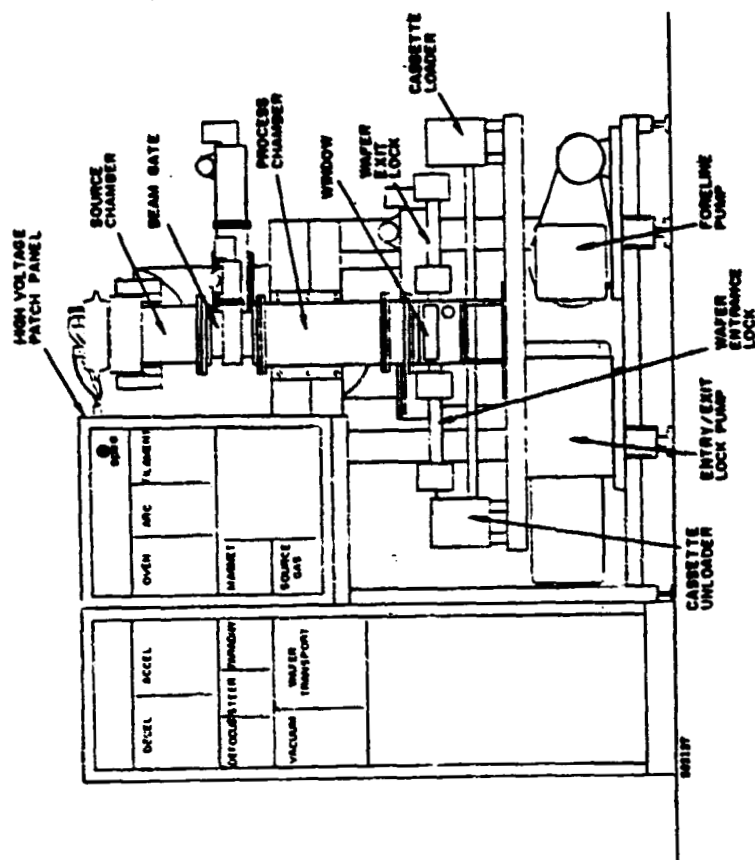
Solar-Cell Ion Implanter Specifications

- Ion Energy: 5 - 20 KeV
- Ion Current: 10 - 15 mA
- Implant L. C., P_1^+ , P_2^+ , etc @ $2.5 \times 10^{15} / m^2$
- Beam Purity: 99% Phosphorous, <0.69% O_2 , <0.3% Other
- Implant Rate: 4 seconds / wafer
- Uniformity: $\pm 2.6\%$, 1σ
- Wafer heating: <150°C rise

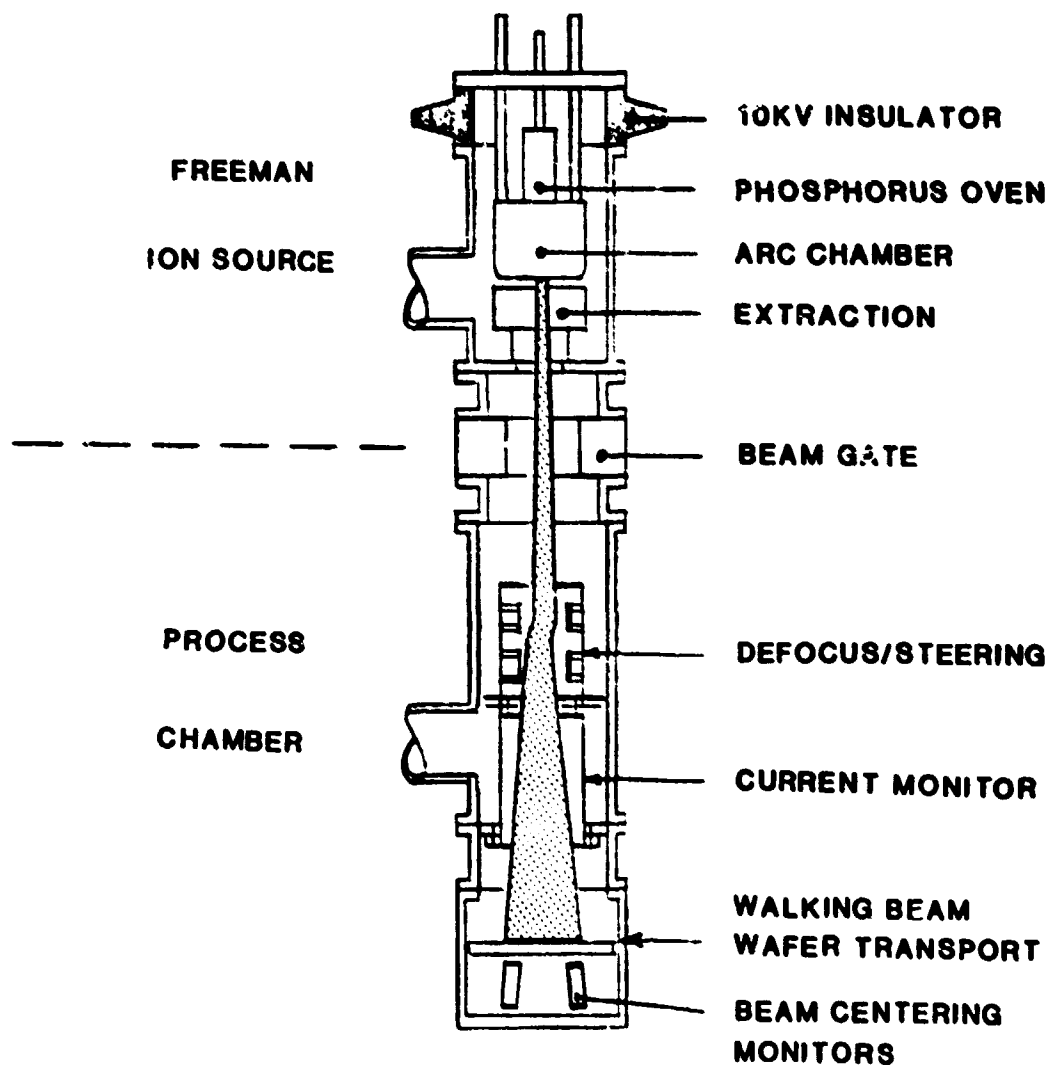
CELL AND MODULE FORMATION RESEARCH AREA

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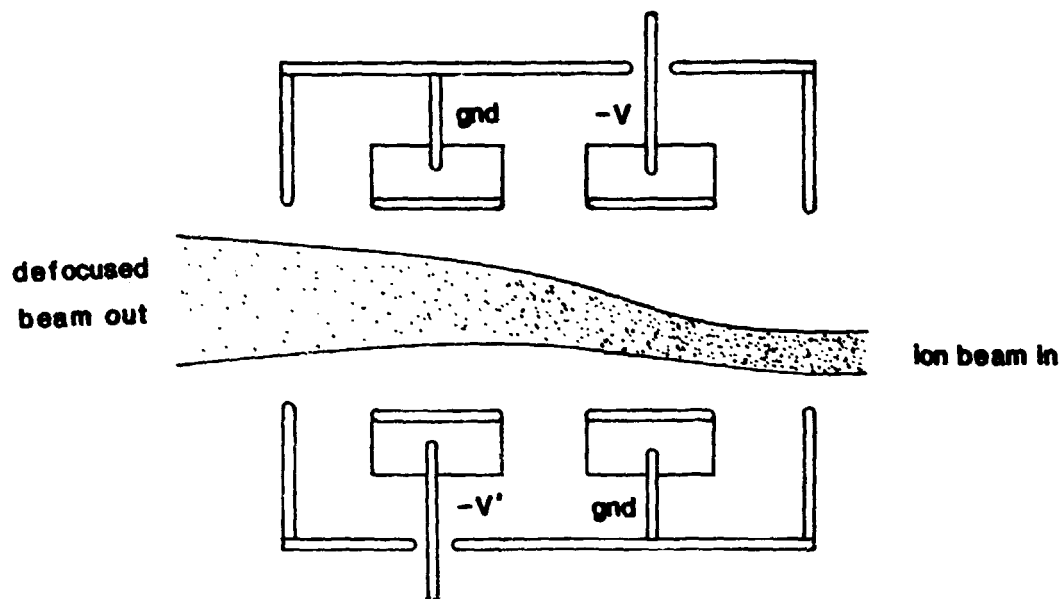
Design of Solar Implanter



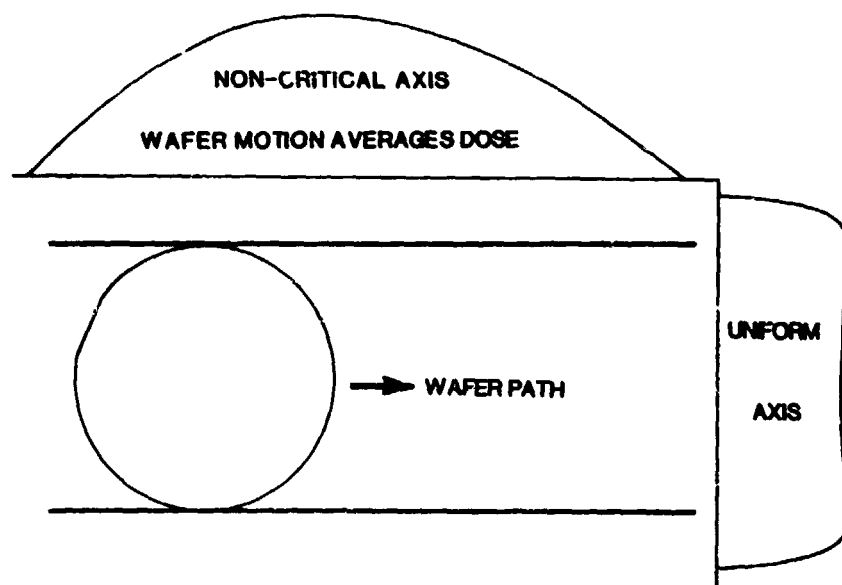
NMA Ion Implanter Beam Path



Electrostatic Beam Defocus



Uniformity Requirements With Walking Beam Track



NMA Ion Implanter Beam Studies

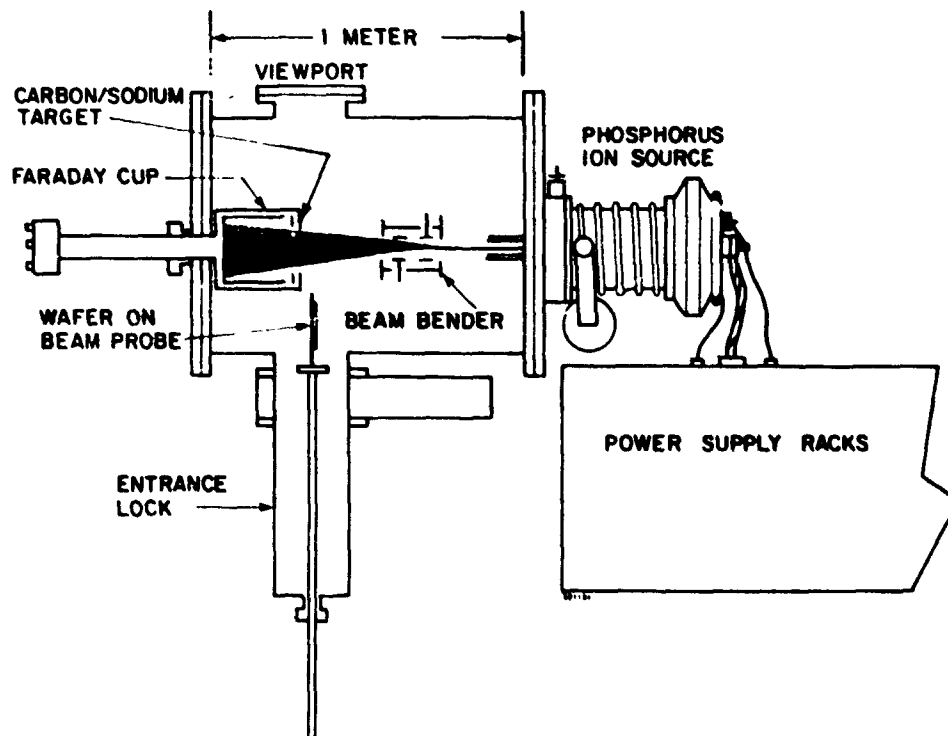
Purpose :

- o High Current Modification
- o Verify Ion Beam Transport
- o Beam Uniformity Measurements
- o Sample Solar Cells

Status :

- o High Current Modification Defined
- o Beam Characteristics Defined
 - Area
 - Uniformity
 - Divergence
 - Energy Dependence
- o Sample Solar Cells In Process

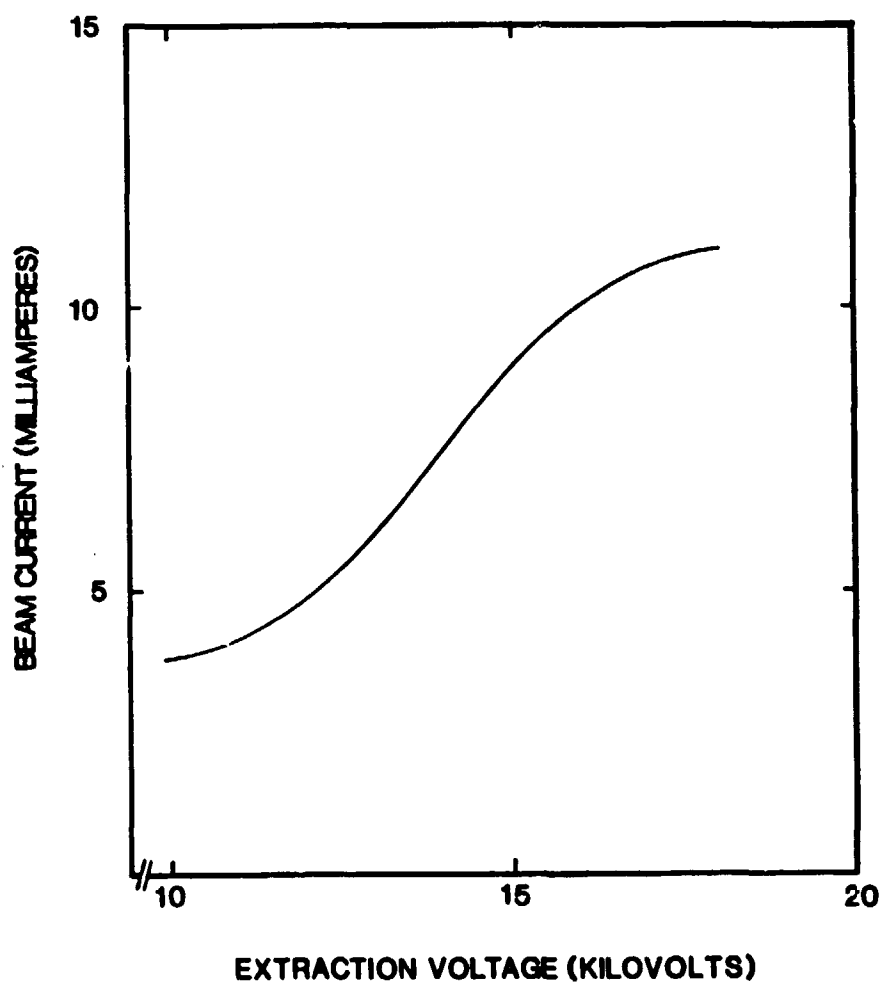
NMA Test Implant Chamber



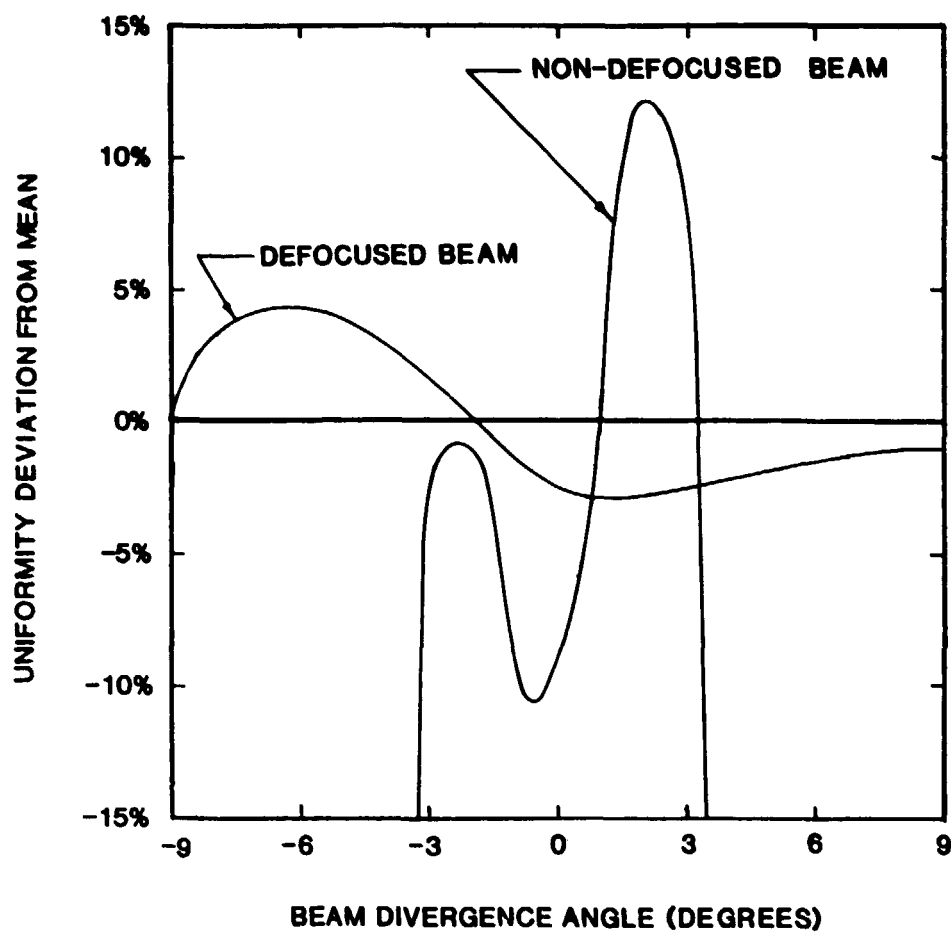
Ion Beam Studies, Phase II

<u>Parameter</u>	<u>Research Goal</u>	<u>Achieved To Date</u>
High Current	10 ma in 10 cm width	11 ma in 12 cm @ 10 KeV
Uniformity on one axis	$\pm 2\frac{1}{2}\%$	Standard Deviation = $\pm 2.6\%$
Energy Range	5 - 20 KeV	5 - 20 KeV
Beam Steering	± 1 cm	Not yet tested

Beam Observed in Phase II Studies at 10 keV



Uniformity Improvement With Defocus



CELL AND MODULE FORMATION RESEARCH AREA

NMA Solar Cells Test Matrix

<u>TEST</u>	<u>IMPLANT ENERGY</u>	<u># OF CELLS</u>	<u>COMMENTS</u>
I. Energy	10 KeV	12	Mass analyzed controls
	10 KeV	12	Standard Energy
	7 1/2 KeV	12	
	5 KeV	12	
	2 1/2 KeV	12	Low Current Beam
II. Wafer Size	10 KeV	2	4" Wafer
	7 1/2 KeV	2	4" Wafer
III. PeBA	10 KeV	10	3" Wafers

Plans

- Continue Beam Focusing and Intensity Experiments
- Detail Design Components
- Fabricate Implanter
- Test and Debug - Sept. - Oct.
- Research with Adv. Sheet Materials

NON-MASS-ANALYZED ION IMPLANTATION

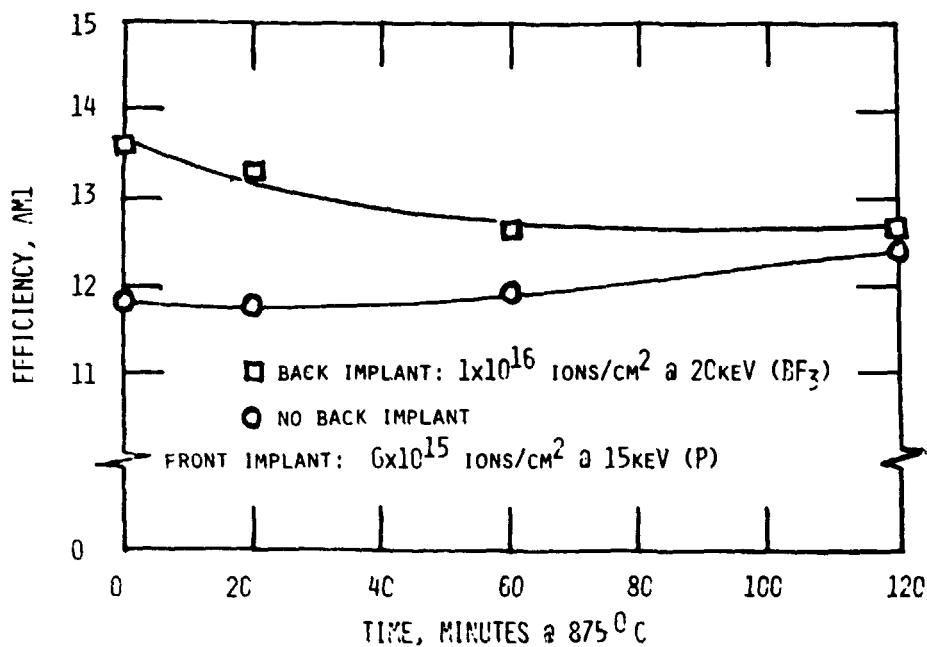
JET PROPULSION LABORATORY

D.J. Fitzgerald

Current Objectives

- FIND EFFECT OF THERMAL PRETREATMENT OF MATERIAL ON CELL EFFICIENCY
- DETERMINE CAUSE OF LOWER V_{oc} OBSERVED IN RECENT N-M-A ION IMPLANTS
- EVALUATE COMBINED N-M-A ION IMPLANTED FRONT JUNCTIONS AND BACK SURFACE FIELD

Effect of Thermal Pretreatment of Material



CELL AND MODULE FORMATION RESEARCH AREA

Evaluation of Low V_{oc} in NMA Implants

PROBLEM:

V_{oc} WITH N-M-A FRONT IMPLANT INCREASED FROM 500 mV TO 550 mV WITH BF_3 BACK IMPLANT. V_{oc} SHOULD HAVE BEEN 50 mV HIGHER IN BOTH CASES.

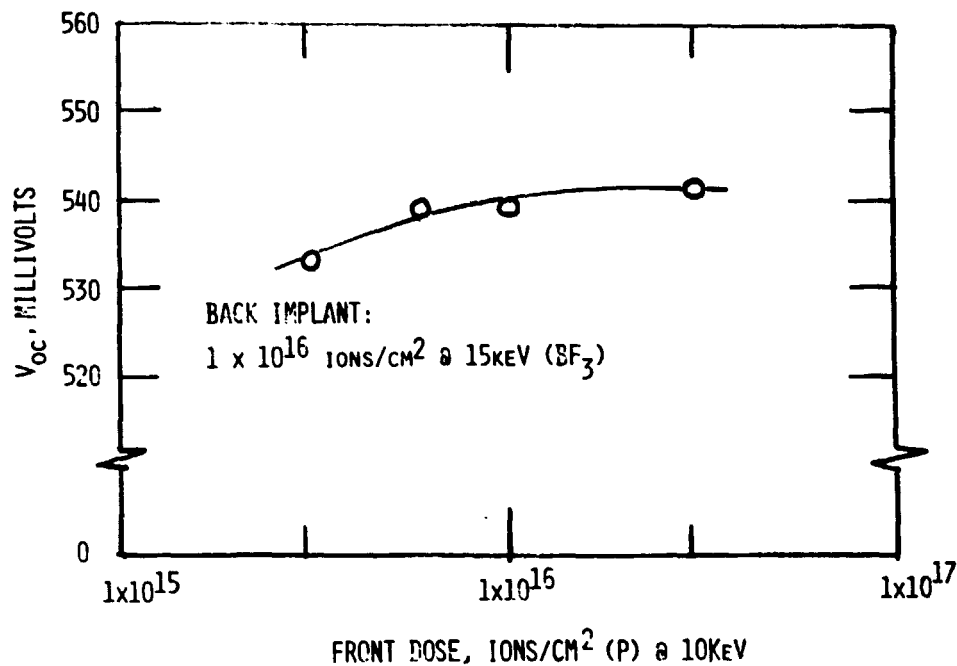
POSSIBLE CAUSES:

- (A) BAD ACTORS SUCH AS IRON IN ION BEAM
- (B) INADEQUATE FRONT JUNCTION DOSE
- (C) POOR BACK CONTACT (NON-OHMIC)
- (D) INADEQUATE BACK SURFACE FIELD (DEPTH, DOSE, BORON ACTIVATION, ETC.)

APPROACH:

- (A) CHANGED S.S. MASKS TO GRAPHITE
- (B) EVALUATED EFFECT OF VARYING FRONT DOSE
- (C) TESTED SAMPLES FOR SHOTTKY BARRIER
- (D) TESTED FOR PRESENCE OF BACK SURFACE FIELD

Effect of Varying Front Dose



- FRONT STRIPPED SAMPLES INDICATED NON-OHMIC CONTACT ON BACK OF THOSE WITHOUT BACK IMPLANT
- CELLS WITH BACK IMPLANT STRIPPED OFF WITH NEW GOOD CONTACT INDICATED THAT SMALL BACK SURFACE FIELD WAS PRESENT (<10 mV)
- SPIRF SUGGESTED THAT HIGH TEMPERATURE ANNEAL STEP (15 MINUTES @ 850°C) SHOULD BE EXTENDED TO 30 MINUTES TO ASSURE BORON ACTIVATION

Conclusions

- THERMAL PRE-TREATMENT OF MATERIAL DEPENDS ON PRESENCE OF BACK IMPLANT
- V_{oc} DEFICIENCY MOSTLY DUE TO NON-OHMIC BACK CONTACT - CAUSE NOT UNDERSTOOD
- BACK IMPLANT MADE CONTACT OHMIC BUT RESULTED IN SMALL BACK SURFACE FIELD
- POOR BACK SURFACE FIELD MAY BE DUE TO INSUFFICIENT BORON ACTIVATION

CELL AND MODULE FORMATION RESEARCH AREA

PROCESS RESEARCH: SEMIX SILICON MATERIAL

SOLAREX CORP.

John H. Wohlgemuth

Change in Program Emphasis

FORMERLY: DEVELOPMENT OF COST-EFFECTIVE PROCESS SEQUENCE

TITLE: MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

NOW: RESEARCH TO UNDERSTAND THE MECHANISMS OF PHOTOVOLTAIC CONVERSION
IN SEMICRYSTALLINE SILICON

TITLE: PROCESS RESEARCH OF SEMIX SILICON MATERIAL (PROSSM)

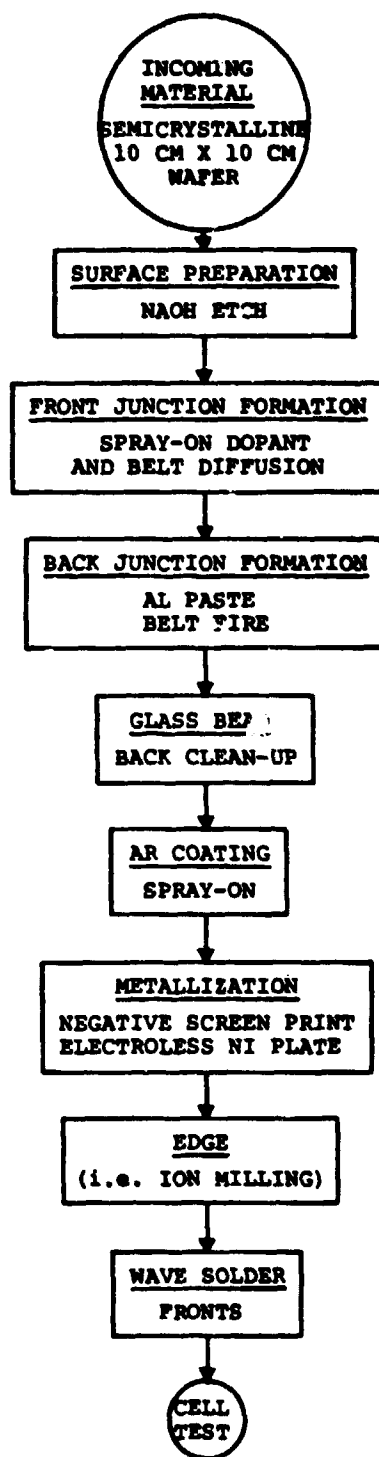
DATE OF CHANGE: FEBRUARY 25, 1982

REPORT ON: THREE MONTHS OF MEPSDU
TWO MONTHS OF PROSSM

MEPSDU Summary

1. COST EFFECTIVE PROCESS SEQUENCE IDENTIFIED
2. COST ANALYSIS OF 6.6MM PER YEAR LINE PROJECTED - \$0.56 PER WATT CELL ADD ON COST
3. THREE SPECIFIC PROCESSES DEVELOPED FOR PROGRAM
 - GLASS BEAD BACK CLEAN-UP
 - WAVE-SOLDERING OF FRONTS)
 - ION MILLING FOR EDGES
4. SPRAY DOPANT - GOOD LABORATORY RESULTS, BUT INCONSIST RESULTS AND SHORT SHELF LIFE. NOT READY FOR PRODUCTION.
5. EQUIPMENT FOR HANDLING AND PROCESSING SOLAR CELLS IS AVAILABLE FOR ALL PROCESS STEPS IDENTIFIED IN THIS PROGRAM.

General Process Description



Cost Estimate

ASSUMPTIONS:

- 10% EFFICIENT CELLS
- 80% YIELDS
- THREE SHIFTS/DAY
- 345 DAYS/YR OPERATION
- PRODUCTION OF 1,000 GOOD CELLS/HR = 6.6 MW PER YR
- IPEG2 COEFFICIENTS

	EQUIP	EQUIP LIFETIME YRS	FT ²	WORKERS/ SHIFT	DEAB	MATS/YR	UTIL/YR
ETCH	65,000	5	200	1	70400.	\$ 25105	\$ 27886
DIFFUSION	173,000	10	504	1	70400.	48900	18307
BSF FORM	83,000	10	328	1/2	33000.	57017	8571
BACK CLEANUP	138,000	3	288	1	70400.	1.490	64738
AR COAT	104,000	10	224	1/2	33000.	73098	13743
RESIST PRINT	126,000	10	392	1	70400.	282307	6145
NI PLATE	50,000	5	378	1	70400.	282090	45248
ION MILL	135,000	10	200	1	65686.	5880	2468
WAVE SOLDER	100,000	5	400	1	65686.	70268	6285
TEST	55,000	10	150	2	150543.	0	1130
	\$1,029,000		3064 ft ²	10	699,915./yr	\$862,255/yr	\$194,521/yr

CELL AND MODULE FORMATION RESEARCH AREA

ORIGINAL PRICE IS
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Cost per Watt

	<u>C1 x EQUIP</u>	<u>FT² x 109</u>	<u>2.1 x DLAB</u>	<u>1.2 x MATS</u>	<u>1.2 x UTIL</u>	
	<u>6.6 E-6</u>	<u>6.6 E-6</u>	<u>6.6 E-6</u>	<u>6.6 E-6</u>	<u>6.6 E-6</u>	<u>TOTALS</u>
ETCH	.0064	.0033	.0224	.0046	.0050	.0417
DIFFUSION	.0136	.0083	.0224	.0089	.0033	.0565
BSF FORM	.0065	.0054	.0105	.0104	.0016	.0344
BACK CLEANUP	.0174	.0048	.0224	.0029	.0118	.0593
AR COAT	.0082	.0037	.0105	.0133	.0025	.0382
RESIST PRINT	.0099	.0065	.0224	.0513	.0011	.0912
NI PLATE	.0049	.0062	.0224	.0513	.0082	.0930
ION MILL	.0106	.0033	.0209	.0011	.0004	.0363
WAVE SOLDER	.0098	.0066	.0209	.0128	.0011	.0512
TEST	<u>.0043</u>	<u>.0025</u>	<u>.0479</u>	<u>.0000</u>	<u>.0002</u>	<u>.0549</u>
	.0916	.0506	.2227	.1566	.0352	.5567

ALL COSTS ARE EXPRESSED IN DOLLARS

Wave Soldering

- WITH PROPER SPEEDS, TILT ANGLE AND WAVE CELLS EXCEEDED DIPPED CELLS IN PERFORMANCE.
- SIMPLE IN-LINE FOAM FLUXER WORKS WELL.
- WAVE SOLDERING OF BOTH SIDES DID NOT WORK. FIRST SIDE PEELED OFF DURING SOLDERING OF SECOND SIDE.
- SOLAREX HAS ORDERED PRODUCTION MACHINE.

CELL AND MODULE FORMATION RESEARCH AREA

Spray AR Coating

- DETAILED TEMPERATURE TIME EXPERIMENTS

TEMPERATURE RANGE	400 - 410°C
TIME	45 SECOND PREHEAT
	5 SECOND SPRAY
	NO POST SPRAY HEATING

- RESULTS IN EXCELLENT QUALITY AR THAT IS READILY REMOVED IN FUMIC HF IN PATTERN AREA

Edging

- SAND BLASTING - GOOD THRUPUT BUT PROCESS IS VERY SENSITIVE TO OPERATIONAL PARAMETERS
- DIFFUSION/PLATING BARRIERS - FUMIC HF ATTACKS MOST OF THE STANDARD MATERIALS
- ION MILLING REMAINS BEST CANDIDATE ALTHOUGH REQUIRES OPTIMIZATION

Spray Dopant (Emulsitone)

- SHORT SHELF LIFE - BREAKDOWN OF VINYL ACETATE PRODUCING ACETIC ACID
- VERY SENSITIVE TO SPRAY CONDITIONS - OVERSPRAYING MEANS YOU CAN'T REMOVE OXIDE
- INCONSISTENCY FROM BATCH TO BATCH

SOME BATCHES LASTED 2-3 MONTHS, OTHER DEGRADED IN LESS THAN ONE MONTH

SOME BATCHES WERE SUCCESSFUL ON MOST RUNS, OTHERS WERE MORE SENSITIVE TO SPRAY CONDITIONS

- CANNOT RECOMMEND FOR PRODUCTION NOW

CELL AND MODULE FORMATION RESEARCH AREA

PROSSM Program

1. PREPARE REVISED PROGRAM PLAN
2. PREPARE SUMMARY REPORT OF MEPSDU
3. INITIATE EFFORT TO UNDERSTAND MECHANISMS CONTROLLING EFFICIENCY IN SEMIX MATERIAL

Two Experiments Under Way

1. USING 10 CM X 10 CM WAFER TO PRODUCE MATRIX OF 400 0.5 CM X 0.5 CM SOLAR CELLS. EVALUATE PERFORMANCE (V_{OC} , I_{SC} , P_{MAX} , DIODE FACTOR, ETC.) AS A FUNCTION OF MACROSCOPIC POSITION ON BRICK AND AS INFLUENCED BY MICROSCOPIC, LOCAL STRUCTURE SUCH AS GRAIN BOUNDARIES, TWINS, ETC.
2. FABRICATING MATRIX OF SAMPLES AT VARIOUS BULK RESISTIVITIES IN THICKNESS FROM 300 MICRONS DOWN TO 50 MICRONS. EVALUATE AND ANALYZE RESULTANT CELLS TO DETERMINE DEPENDENCE OF MINORITY CARRIER DIFFUSION LENGTH ON BULK RESISTIVITY AND TO DETERMINE THE MECHANISMS CONTROLLING VOLTAGE.

CELL AND MODULE FORMATION RESEARCH AREA

MEPSDU

WESTINGHOUSE ELECTRIC CORP.

C.M. Rose

Goals and Approach

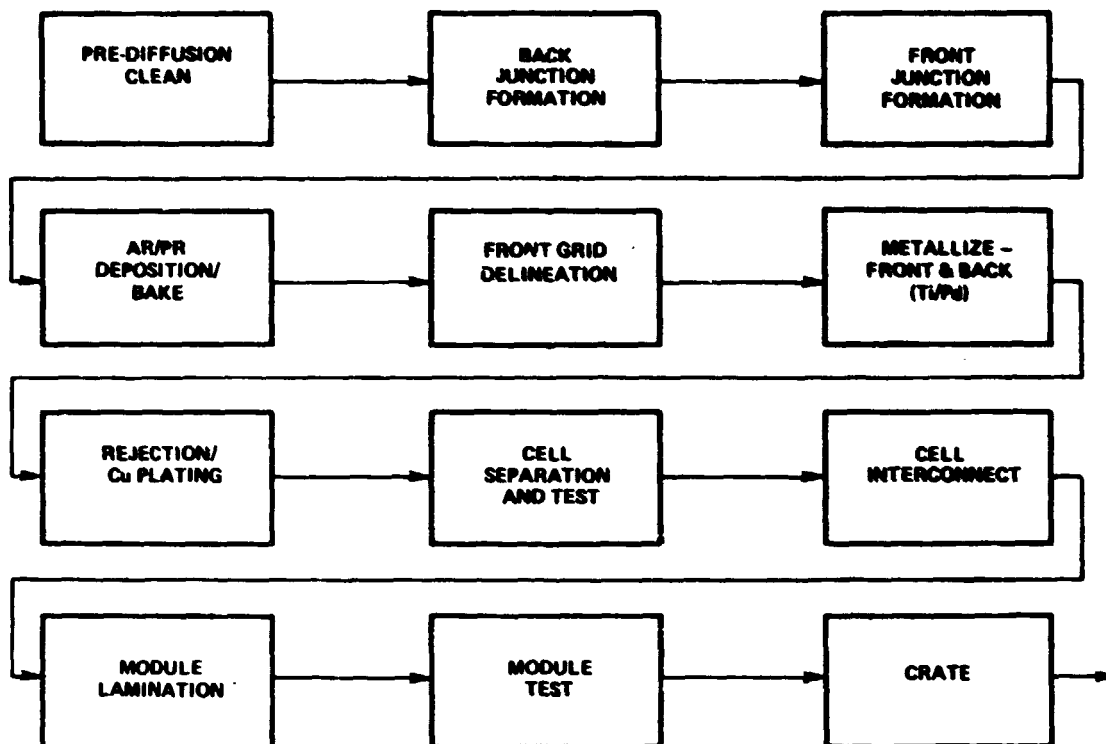
- DESIGN MODULE MEETING JPL 5101-138 SPECIFICATIONS
- SELECT AND VERIFY PROCESS SEQUENCE FOR FABRICATING MODULES
- DESIGN AND BUILD A TEST FACILITY TO FABRICATE MODULES USING SELECTED PROCESS SEQUENCE
- PERFORM TECHNICAL FEASIBILITY EXPERIMENTS
- ACCEPTANCE AND QUALIFICATION TESTING OF MODULES PRODUCED
- DETERMINATION OF 1986 MODULE PRODUCTION COSTS

Milestone Schedule

<u>MILESTONE</u>	<u>CURRENT PROGRAM PLAN</u>
START DATE	NOV. 26, 1980
PRELIMINARY DESIGN REVIEW	MAR. 3, 1981
PROTOTYPE MODULE DESIGN REVIEW	JULY 14, 1981
MEPSDU DESIGN REVIEW	MAY 15, 1982
ECONOMIC ANALYSIS REVIEW	SEPT. 14, 1982
MEPSDU INSTALLATION	JAN. 31, 1983
TECHNICAL FEASIBILITY EXPERIMENTS	DEC. 15, 1983
FINAL REPORT	DEC. 31, 1983

CELL AND MODULE FORMATION RESEARCH AREA

Baseline Process Sequence



Prototype Module Fabrication Progress

<u>DATE</u>	<u>AVG. CELL EFFICIENCY</u>	<u>MODULE EFFICIENCY</u>
MAR. 1981	10.8 %	7.5 %
SEPT. 1981	10.5	9.0
OCT. 1981	12.3	10.6
DEC. 1981	12.7	11.2

CELL AND MODULE FORMATION RESEARCH AREA

Module Environmental Tests

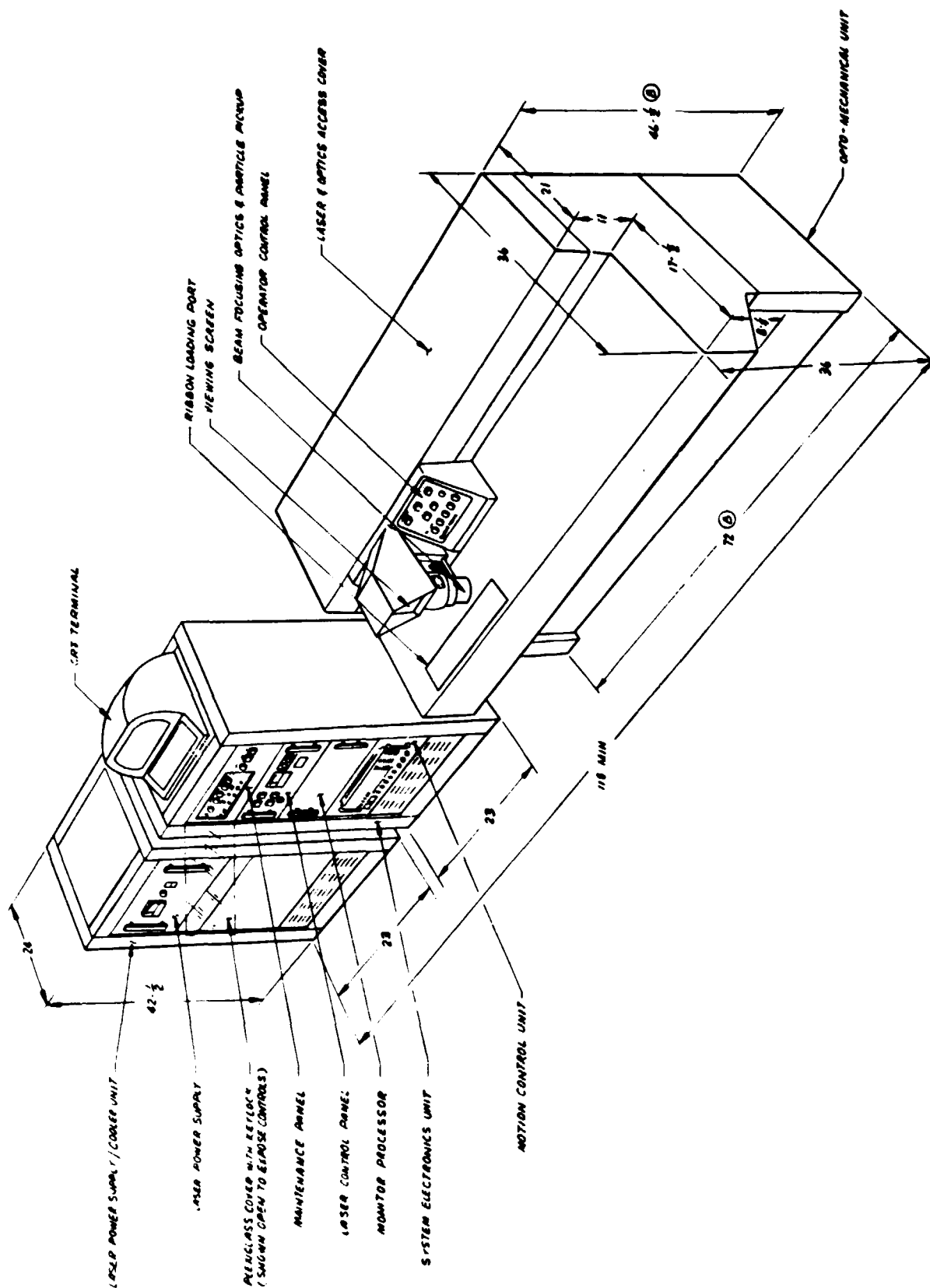
<u>TEST</u>	<u>RESULT</u>
THERMAL CYCLES (250)	NO MEASURABLE DEGRADATION
5101-138 HUMIDITY CYCLES	NO MEASURABLE DEGRADATION, NO OBSERVABLE DELAMINATION
CELL SHADING TESTS	NO MEASURABLE TEMP. INCREASE
CELL INTERCONNECT FAILURE	NO MEASURABLE POWER DEGRADATION WITH MULTIPLE INTERCONNECT FAILURES
POS./NEG. WIND LOAD TESTS	NO DAMAGE
HAIL IMPACT	NO DAMAGE AT IMPACT ENERGY UP TO 5 TIMES DESIGN LEVELS

25 MW/yr Production Facility Cost Analysis

<u>PROCESS STEP</u>	<u>PROCESS</u>	<u>VALUE ADDED (1980 \$/WATT)</u>	<u>% TOTAL</u>
1	PREPARE INPUT WEB	0.353	49.73
2	BORON DIFFUSION	0.032	4.51
3	PHOSPHOROUS DIFFUSION	0.023	3.33
4	APPLICATION OF AR/PR	0.016	2.24
5	DEFINE GRID PATTERN	0.017	2.40
6	METALLIZE WEB	0.037	5.18
7	REJECTION AND PLATING	0.037	5.26
8	CELL SEPARATION AND TEST	0.029	4.06
9	CELL INTERCONNECTION	0.026	3.67
10	LAMINATION	0.121	17.02
11	CRATING	0.019	2.62
TOTAL FOR PROCESS — 0.709		<u>1980 \$</u> PEAK WATT	

Automated Laser Scribe

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CELL AND MODULE FORMATION RESEARCH AREA

DENDRITIC WEB SILICON

WESTINGHOUSE ELECTRIC CORP.

Goals

- **ESTABLISH FEASIBILITY OF SUBSTITUTING LIQUID DOPANTS FOR GASEOUS DIFFUSION PROCESS**
- **OPTIMIZE LIQUID DOPANT DRIVE-IN PARAMETERS**
- **OPTIMIZE LIQUID APPLICATION TECHNIQUE FOR:**
 - **DOPANTS**
 - **SiO₂ PRECURSOR DIFFUSION MASKS**
 - **AR/PR COATINGS**
- **ESTABLISH FEASIBILITY OF SUBSTITUTING ION IMPLANTATION FOR GASEOUS DIFFUSION PROCESS**

Liquid Dopants: Expected Advantages

- **LESS EXPENSIVE EQUIPMENT**
- **LESS EXPENSIVE CHEMICALS**
- **FEWER CLEANING OPERATIONS**
- **SIMPLIFIED PROCESS CONTROLS**
- **AUTOMATABLE PROCESS**
- **BASELINE SEQUENCE COMPATIBILITY**

CELL AND MODULE FORMATION RESEARCH AREA

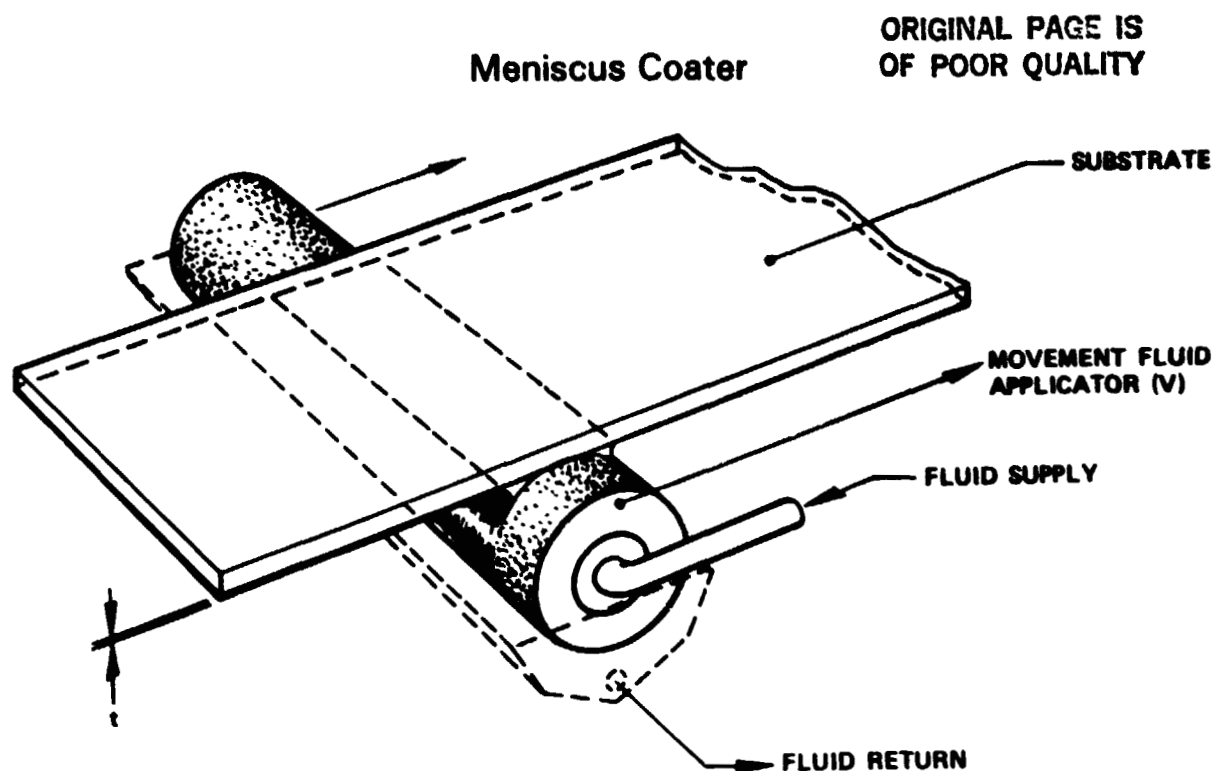
Liquid Dopants: Experimental Approach

- **DIFFUSION PARAMETER OPTIMIZATION**
 - **TIME/TEMPERATURE FOR LIQUID BORON DRIVE**
 - **TIME/TEMPERATURE FOR LIQUID PHOSPHORUS DRIVE**
 - **TIME/TEMPERATURE FOR SIMULTANEOUS DRIVE**
- **LIQUID APPLICATION TECHNIQUE INVESTIGATION**
 - **DIPPING**
 - **SPRAYING**
 - **MENISCUS COATING**
- **LIQUID SiO₂ PRECURSOR FEASIBILITY DETERMINATION**
- **COST ANALYSIS**

Liquid Dopants: Experimental Tools

- **CELL FABRICATION – LIGHT & DARK IV PARAMETERS**
- **SHEET RESISTIVITY**
- **JUNCTION PROFILES**

CELL AND MODULE FORMATION RESEARCH AREA



Ion Implantation: Expected Advantages

- HIGHER CELL EFFICIENCY
- IMPROVED CELL PROPERTY UNIFORMITY
- DRY, ENVIRONMENTALLY BENIGN, PROCESSING
- BASELINE SEQUENCE COMPATIBILITY

CELL AND MODULE FORMATION RESEARCH AREA

Conclusions

- (W) MEPSDU WORK STOPPED FEB. 10
- ALL PROGRAM TASKS ON SCHEDULE AND IN BUDGET
- MODULE PASSED ALL ENVIRONMENTAL SPECIFICATIONS
- PROJECTED PRODUCTION COSTS MET 70¢/WATT OBJECTIVE
- REDIRECTED TASKS
 - FINAL MEPSDU REPORT
 - LIQUID DOPANTS AND APPLICATOR STUDY
 - ION IMPLANTATION WORK
- REVISED PROGRAM PLAN SUBMITTED TO JPL

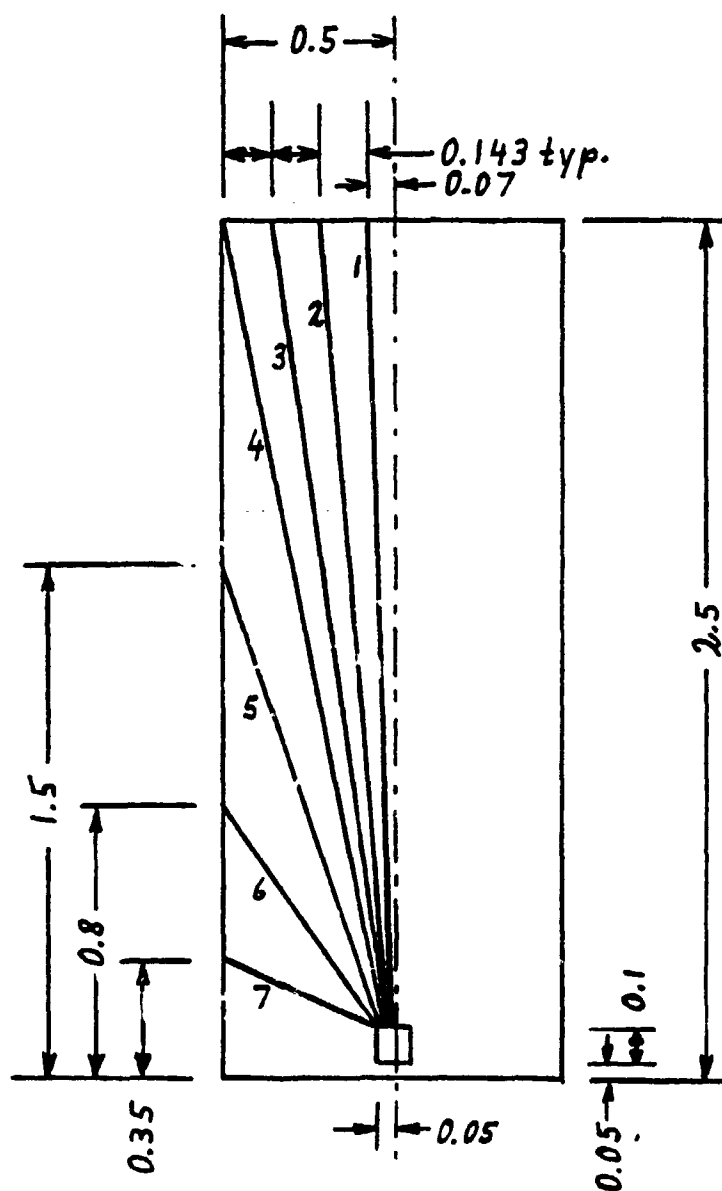
PHOTOVOLTAIC ASSESSMENT

UNIVERSITY OF PENNSYLVANIA

M. Wolf

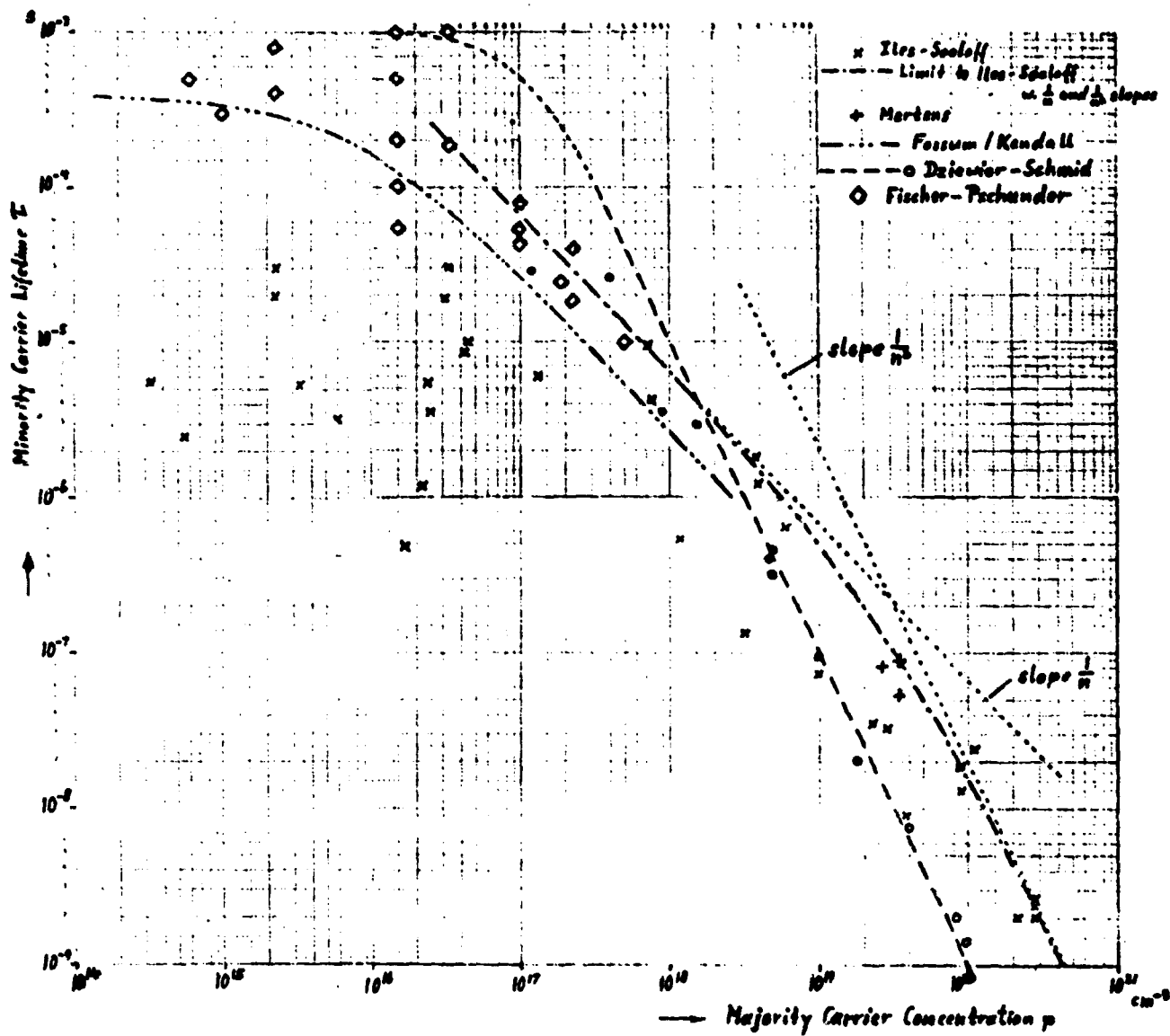
Approximate Westinghouse Grid Line Pattern

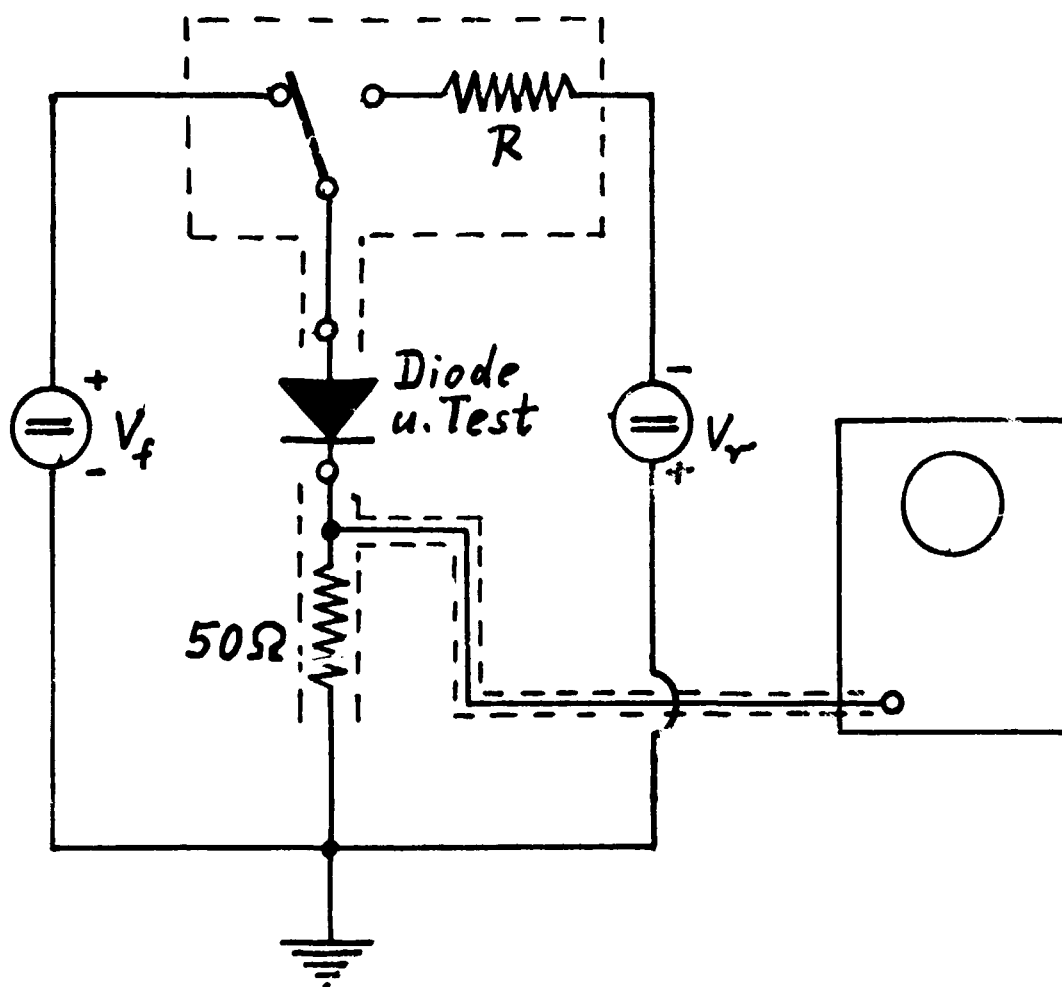
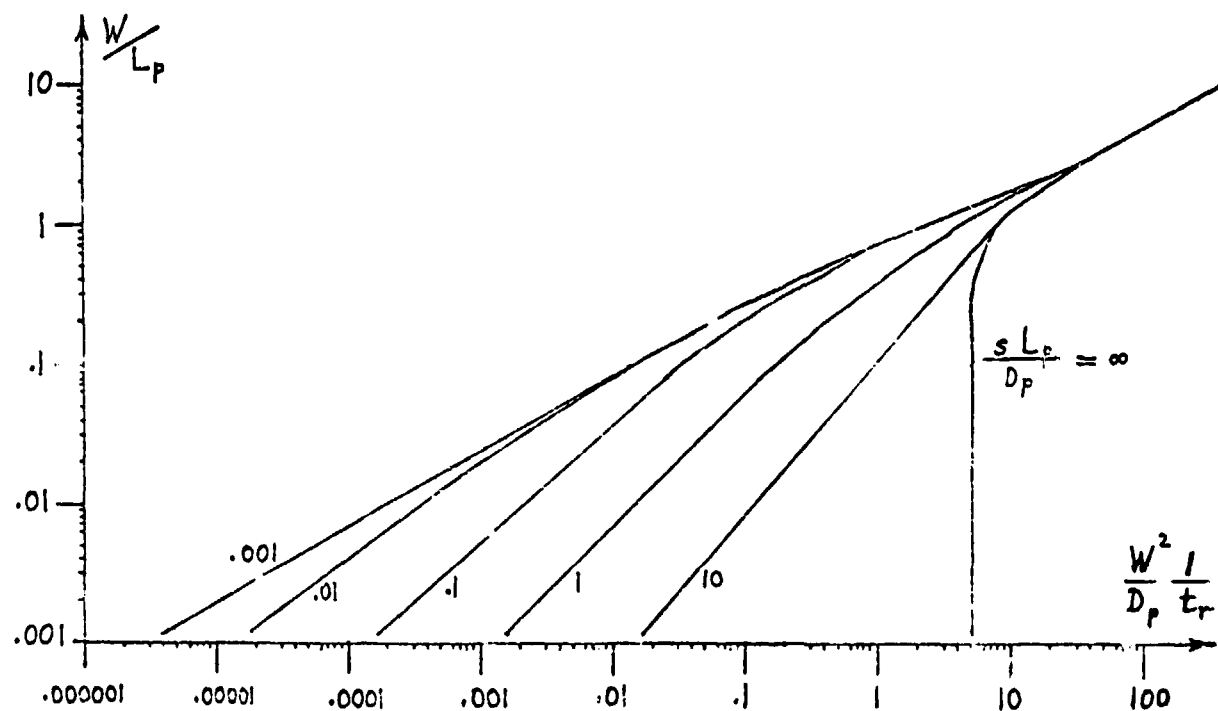
(All Dimensions in cm)

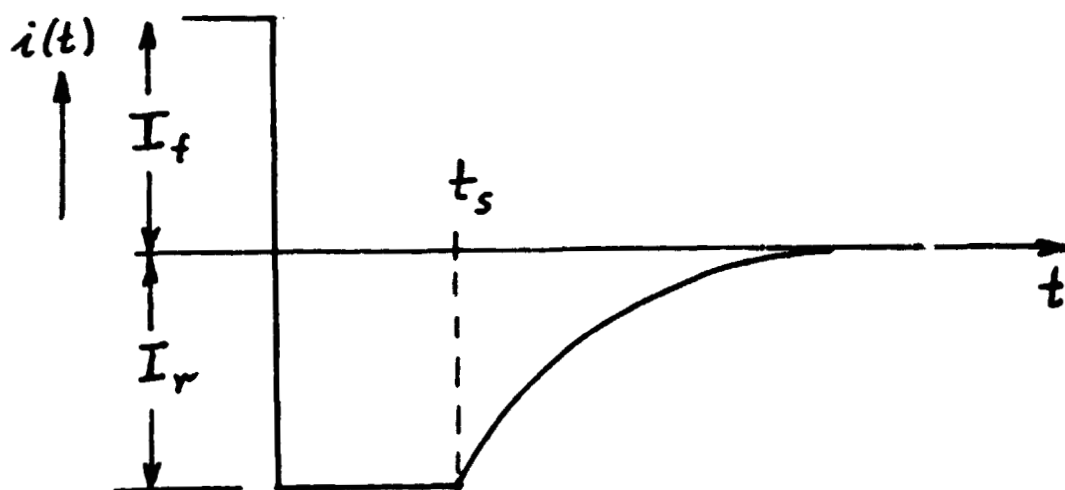
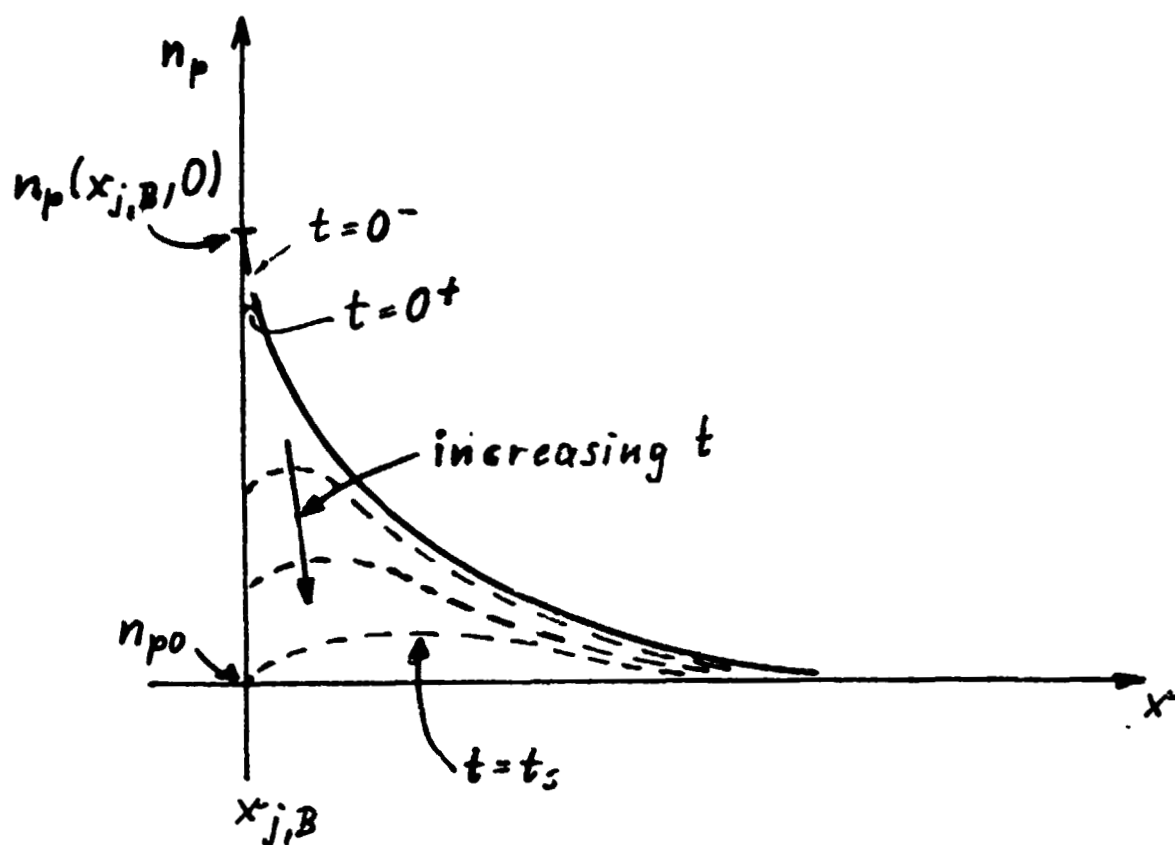


CELL AND MODULE FORMATION RESEARCH AREA

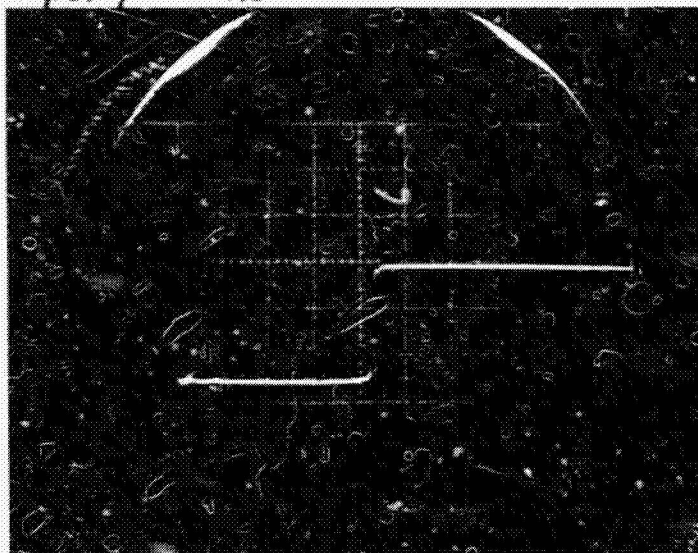
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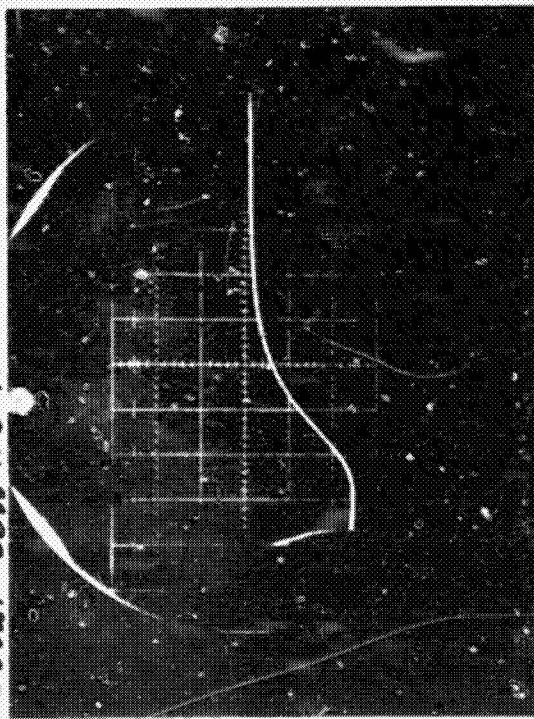


Epoxy Diode



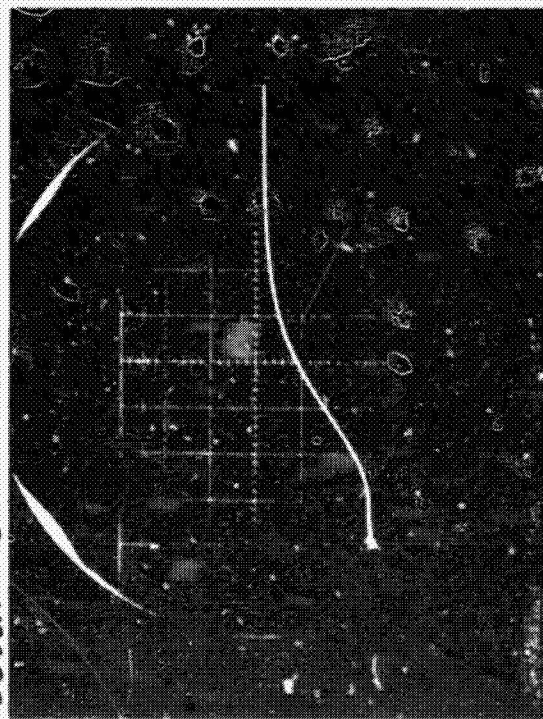
$I_f = I_r = 100 \text{ mA}; 1 \mu\text{s}/\text{div.}$

Solar Cell #51A



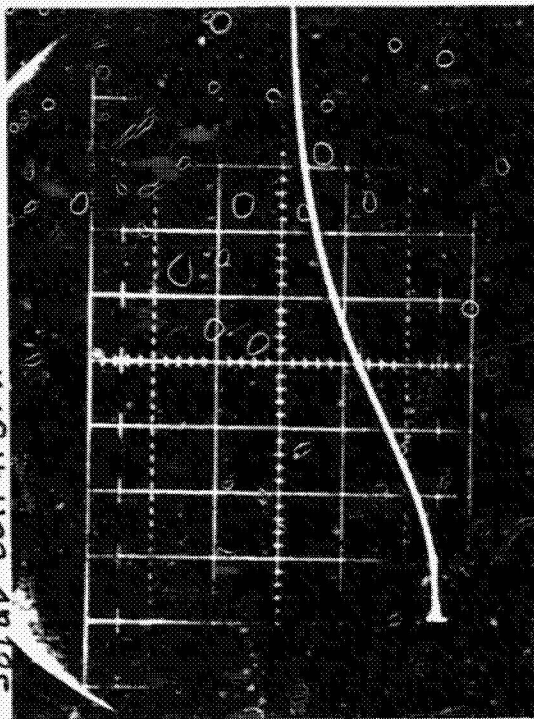
$I_f = I_r = 250 \text{ mA}$; $2 \mu\text{s}/\text{div}$ horiz.

Solar Cell #51A



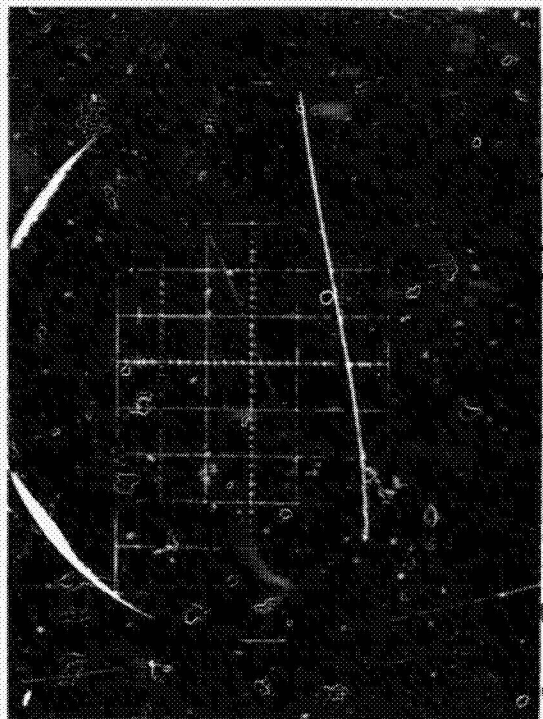
$I_f = I_r = 100 \text{ mA}$; $2 \mu\text{s}/\text{div}$ horiz.

Solar Cell #51A

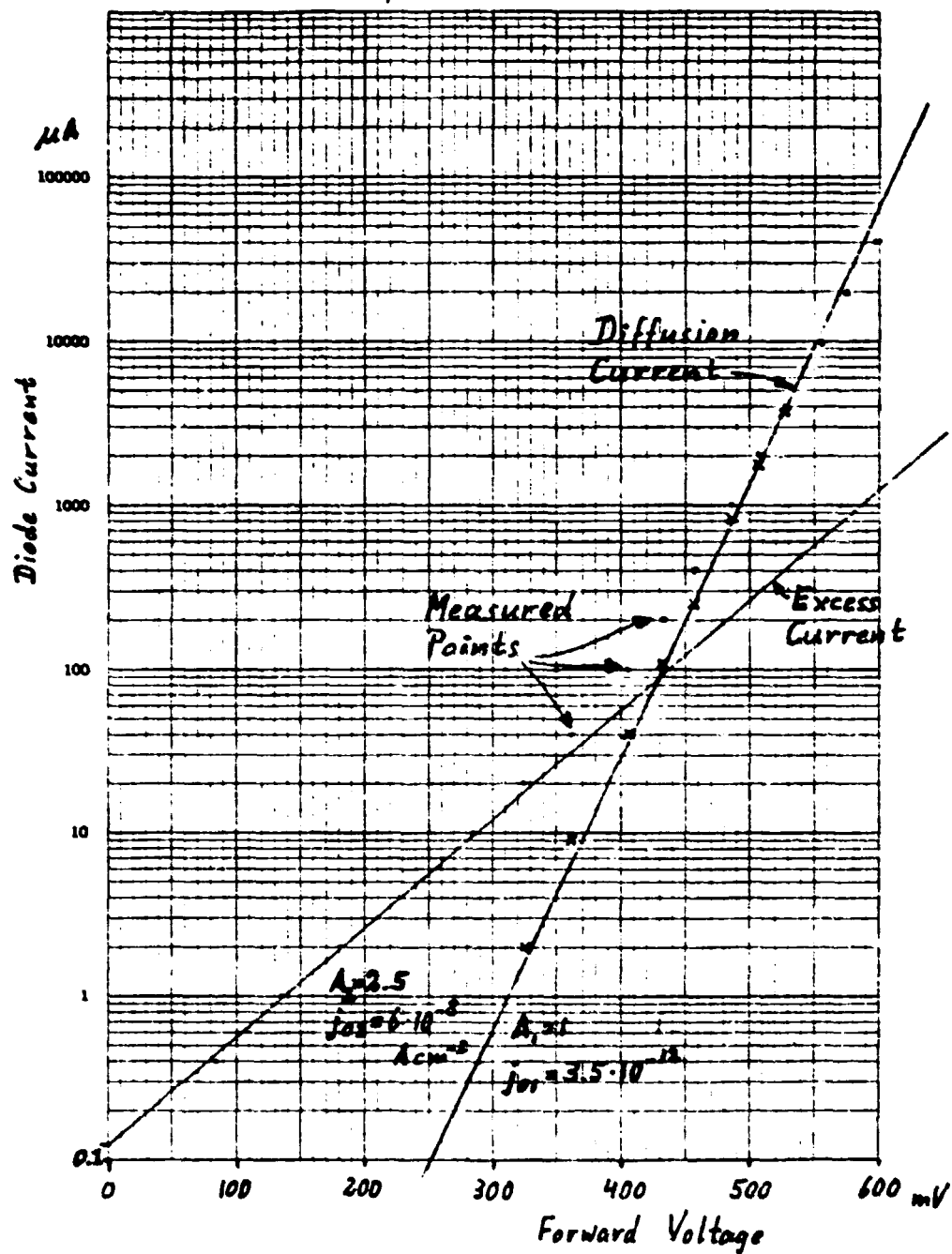


$I_f = I_r = 25 \text{ mA}$; $2 \mu\text{s}/\text{div}$ horiz.

Solar Cell #51A

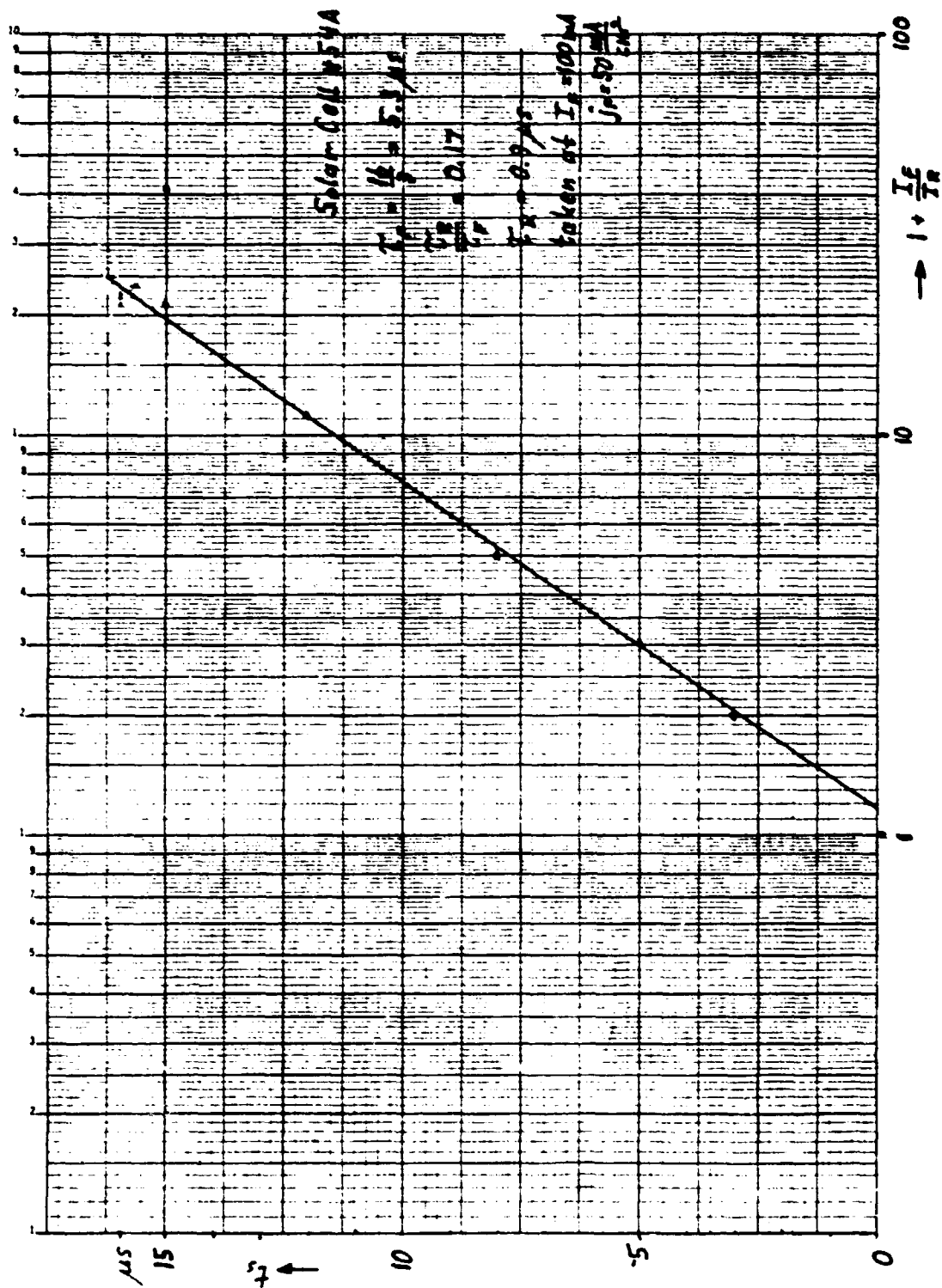


$I_f = I_r = 10 \text{ mA}$; $2 \mu\text{s}/\text{div}$ horiz.

MODEL Solar Cell # 51A; $T = 296.5 \text{ K}$ DATE 3-26-82 MJD.

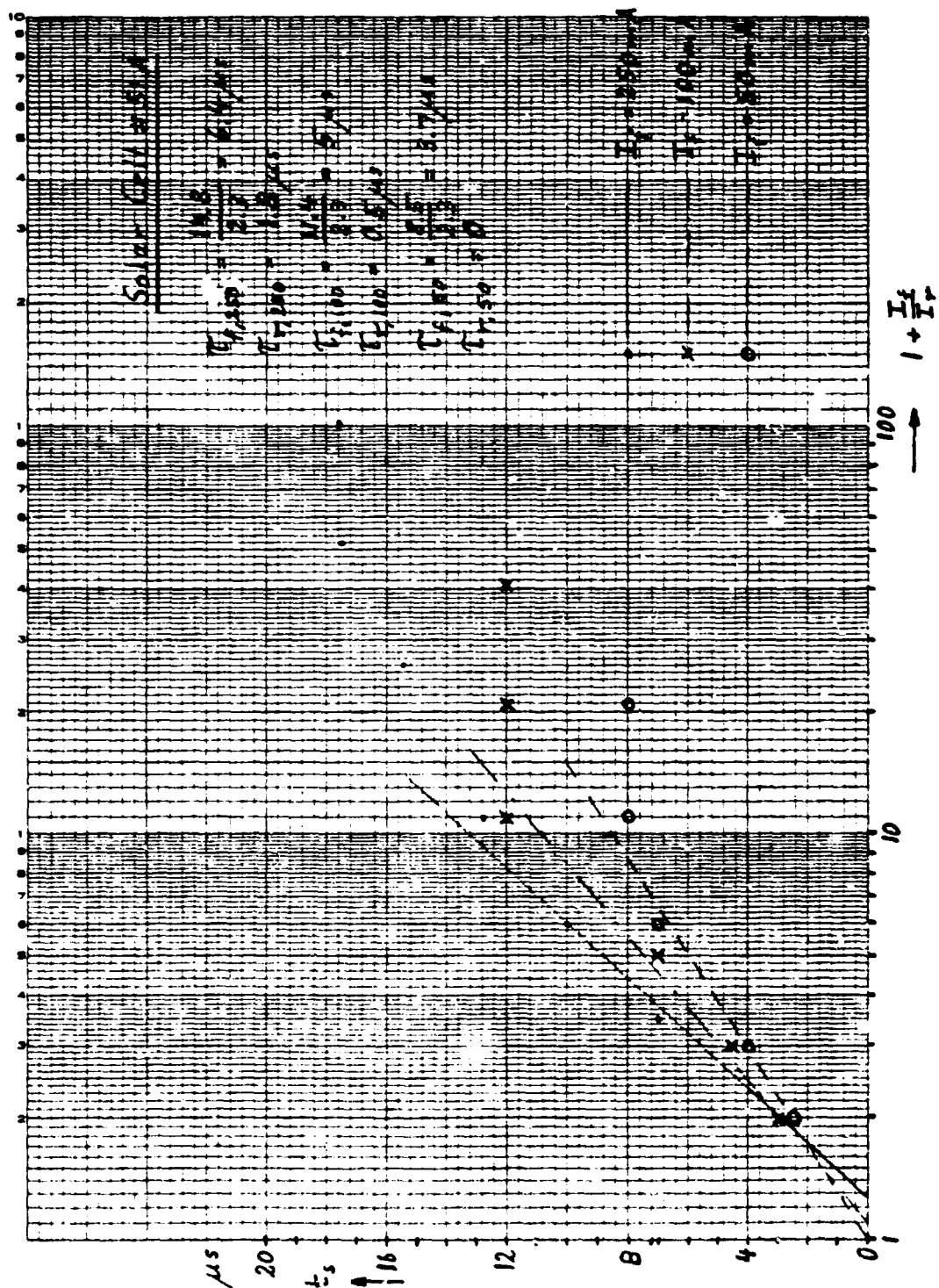
CELL AND MODULE FORMATION RESEARCH AREA

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CELL AND MODULE FORMATION RESEARCH AREA

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ENGINEERING SCIENCES AREA AND MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

R.G. Ross, Jr., and L.D. Runkle, Chairmen

Presentations from the Engineering Sciences Area and Module Performance and Failure Analysis Area were offered in a joint technology session; summaries of the presentations are given below.

C. C. Gonzalez (JPL) presented an update of photovoltaic-array/power-conditioner interface studies. The objective of these studies is to characterize flat-plate arrays by determining significant array operating parameters such as optimum operating voltage. The characterization was obtained by calculating the effect of array/power-conditioner interface parameters on system annual energy production by performing an hour-by-hour array energy simulation using SOLMET weather tapes. The update included correlations of previously reported results with weather atlas data and additional sensitivity studies including effects of array test angle. Also discussed was the effect of power-conditioner efficiency on array annual power production.

George Hart of the Massachusetts Institute of Technology (MIT) described an experiment conducted at the MIT Lincoln Laboratories (MIT-LL) Northeast Residential Experiment Station (NE RES) by MIT-LL and JPL to evaluate different operating-point strategies, such as constant voltage and pilot cells, and to determine array energy losses when the array is operated off the maximum power point. Initial results over a test period of three and a half weeks showed a 2% energy loss when the array is operated at a fixed voltage.

Charles Cox of MIT-LL reviewed degraded-array studies conducted at NE RES that used a range of simulated common types of degraded I-V curves. The additional amount of energy lost at fixed array voltages was compared with outputs from an ideal maximum-power tracker. In a wide variety of degraded arrays the studies found insignificant increases in annual energy losses in tracking arrays.

R. W. Weaver (JPL) described the instrumentation installed at the JPL field-test site to obtain the irradiance data. These include precision spectral pyranometers, normal-incidence pyrhemometers, filtered radiometers, LiCor pyranometers and assorted reference cells. These instruments are appropriately mounted on a sun tracker, horizontally or tilted at 34 degrees. Data is taken every five minutes from sunup to sundown, and the turbidity coefficient, water vapor content and air mass are calculated. It was noted that the turbidity coefficient is a good indicator of the diffuse radiation fraction in the normal plane, but gives poor correlation with the ratio of total horizontal to total tilted irradiance.

C. H. Seaman (JPL) described experiments using an optical filter to adjust the spectral irradiance of the large-area pulsed solar simulator (LAPSS) to AM1.5. A "round-robin" set of intercomparison tests using four different reference cells with matched and unmatched red-blue ratios and using the LAPSS both with and without the Schott GG-4 filter produced the following

ENGINEERING SCIENCES AREA MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

conclusions: the red-blue ratio is not a satisfactory criterion for matching reference cells with solar modules for power measurements, and if the LAPSS is used with a filter adjusting the spectral irradiance to approximate AM1.5, then the reference cell need not be matched spectrally with the module.

A. H. Wilson (JPL) reviewed contractor and in-house activity associated with residential-array research. A roof-mounted support structure, designed as a research model and fabricated at JPL, was reviewed and displayed in the PIM lobby. Features of the model were presented, including its lightweight non-conductive frame, simplified configuration for module installation and removal, and an electrical system design consonant with proposed 1984 National Electrical Code requirements. The model will aid JPL efforts in synthesizing solutions to the technological gaps identified by contractor and JPL studies.

G. R. Mon described recent voltage isolation test results that included voltage probability characterization of 22 as-manufactured materials, including pottants, single-layer and multilayer back-surface polymer films, and multilayer composites. The advantages of using multilayer films was emphasized by exhibiting the increased reliability to be gained at the module level. Preliminary test results from a small sample of aged materials has indicated a higher failure probability at a given operating voltage for aged (vs unaged) materials.

A. Shumka (JPL) reviewed experiments performed on one type of module to determine the relationship between leakage current and temperature. The leakage current between the electrically active part of the module and ground was found to be strongly dependent upon temperature in a module using PVB as an encapsulant. As a result of this and other effects, the specification of the voltage-withstanding test is being reviewed.

A presentation by J. W. Lathrop explained the encapsulated-cell testing approach being used at Clemson University. Findings from earlier tests on unencapsulated cells and differences being pursued in the testing of encapsulated cells were summarized. A total of more than 367 encapsulated cells involving more than 25 different metallization-encapsulation combinations will be tested.

B. H. Otch (JPL) and G. R. Mon (JPL) described in a joint presentation the test program, data reduction methods and initial results of long-duration module testing at Wyle Laboratories (Huntsville, Alabama). Although visual encapsulant degradation occurred on several Block II and III PVB modules from temperature-humidity environments, the loss in peak power was on the order of 5% after 112 days of 85°C/85% RH exposure. Other failure mechanisms that identified the need to increase JPL quality test durations to verify module 20-year field-site capability for U.S. environments were reviewed. The need for an intermediate test condition, between the current 40°C/93% RH and 85°C/85% RH temperature-humidity levels, was also discussed. The new test, together with the 85°C/85% temperature soak tests, would support accurate definition of generic module degradation rates.

PV ARRAY/POWER-CONDITIONER INTERFACE UPDATE

JET PROPULSION LABORATORY

C.C. Gonzalez

Objective

**TO CHARACTERIZE FLAT-PLATE ARRAYS BY DETERMINING SIGNIFICANT
ARRAY OPERATING PARAMETERS:**

- **OPTIMUM OPERATING VOLTAGE**
- **OPERATING VOLTAGE RANGE REQUIRED TO OBTAIN A GIVEN
AMOUNT OF ENERGY ANNUALLY**
- **MAXIMUM POWER AND CURRENT LIMITS REQUIRED TO OBTAIN A
GIVEN AMOUNT OF ENERGY ANNUALLY**
- **MAXIMUM OPEN-CIRCUIT VOLTAGE**
- **CHANGES IN VALUES OF OPTIMUM AND MAXIMUM OPERATING
PARAMETERS WITH ARRAY DEGRADATION**
- **ANNUAL ENERGY OUTPUT VS POWER LEVEL
(USED TO CALCULATE POWER CONDITIONER EFFICIENCY)**

Approach

- Calculate Effect of Array-Power Conditioner
Operational Interface Parameters on System
Annual Energy Production:
 - Annual Energy Based on Hour-by-Hour
Simulation Using Array Temperature and
Irradiance From SOLMET TMY Tapes
 - 26 Site Locations in U.S.
 - All Parameters Normalized to Array
Maximum-Power Parameters at Standard
Operating Conditions (SOC = NOCT, 100 mW/cm²)

Status of Array/PC Interface Studies

- WORK REPORTED LAST PIM
 - OPTIMUM FIXED OPERATING VOLTAGE AND VOLTAGE TRACKING RANGE
 - MAXIMUM POWER AND CURRENT LIMITS
 - MAXIMUM OPEN-CIRCUIT VOLTAGE
- RECENTLY COMPLETED ACTIVITIES
 - CORRELATION OF COMPUTER SIMULATION RESULTS WITH WEATHER ATLAS DATA
 - COMPARISON OF ANALYSIS RESULTS WITH VARIATIONS IN ARRAY TILT ANGLE
 - DEVELOPMENT OF TECHNIQUE FOR USING ARRAY SIMULATION RESULTS TO OBTAIN POWER CONDITIONER EFFICIENCY
 - REPORT FOR SANDIA PCS SPECIFICATION
 - PAPER FOR AS/ISES MEETING (HOUSTON, TX, JULY 1-4, 1982)
 - COORDINATION OF JPL/MIT PCS STUDIES
- FUTURE ACTIVITIES
 - FINAL REPORT IN PREPARATION
 - PROVIDE SUPPORT FOR CONCENTRATOR ANALYSIS

Correlation of Computer Simulation Results With Weather Atlas Data

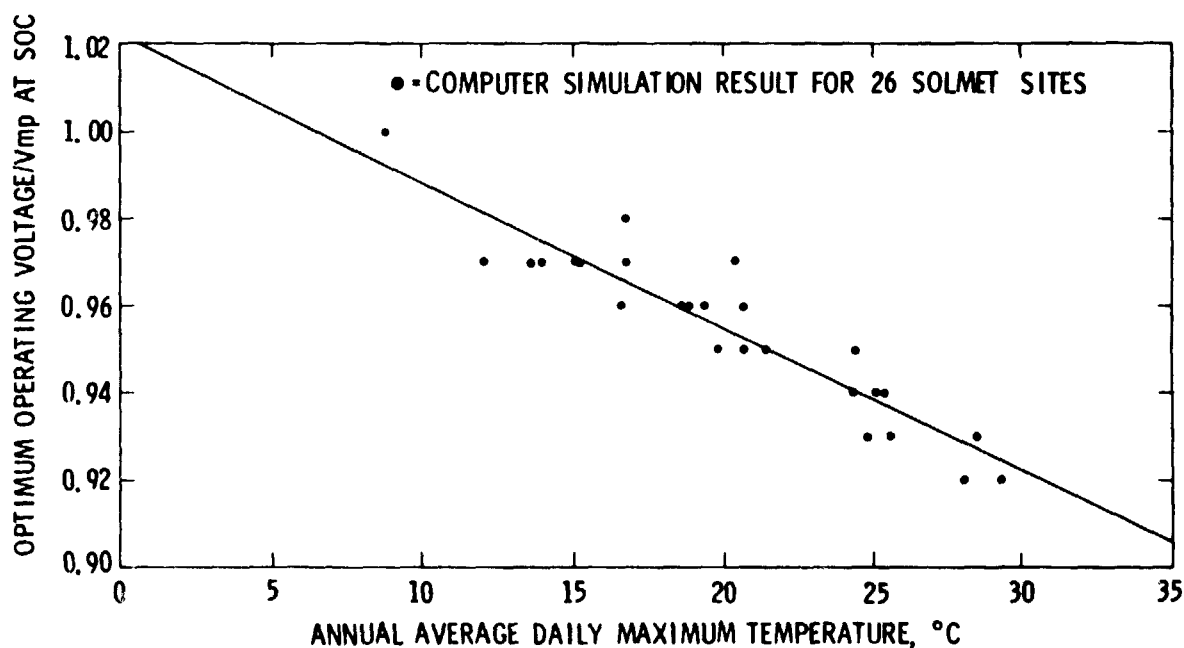
PROBLEM:

- LACK OF HOURLY DATA LIMITS USEFULNESS OF COMPUTER SIMULATION RESULTS
 - OPTIMUM OPERATING VOLTAGE
 - ENERGY LOSS WITH FIXED VOLTAGE OPERATION
 - EFFECT OF FILL FACTOR ON OPTIMUM OPERATING VOLTAGE
 - EFFECT OF FILL FACTOR ON ENERGY LOSS
 - MAXIMUM OPEN-CIRCUIT VOLTAGE

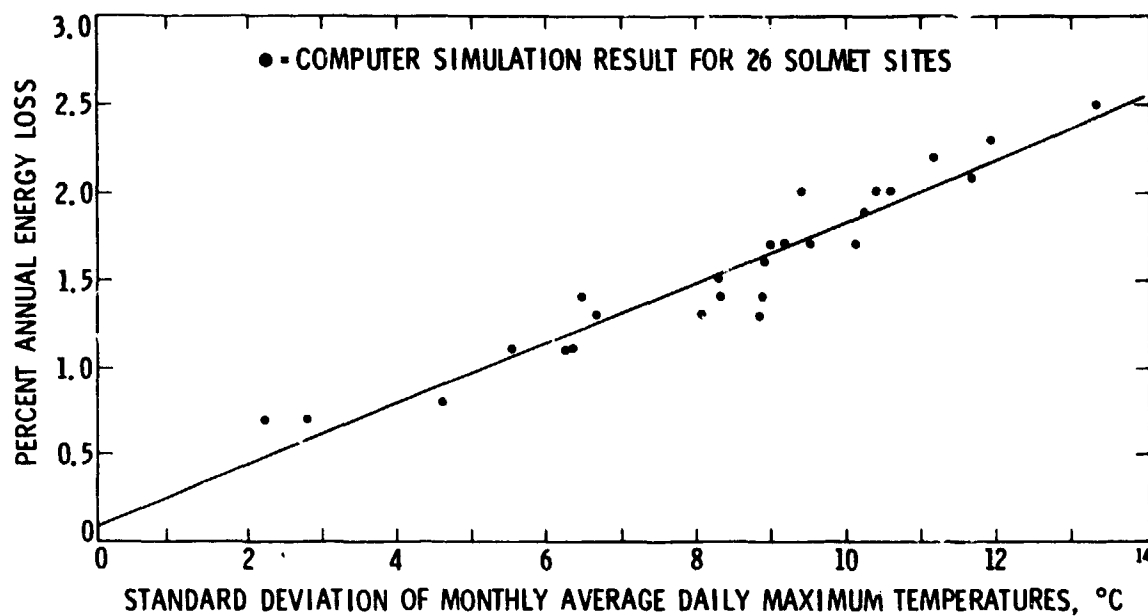
SOLUTION:

- OBTAIN CORRELATIONS WITH VARIOUS WEATHER ATLAS DATA:
 - ANNUAL AVERAGE DAILY MAXIMUM TEMPERATURE
 - STANDARD DEVIATION OF DAILY MAXIMUM TEMPERATURE
 - K_d = DIFFUSE FRACTION OF EXTRATERRESTRIAL SOLAR IRRADIANCE
 - K_d/K_T = DIFFUSE FRACTION OF SURFACE SOLAR IRRADIANCE
 - COLDEST RECORDED TEMPERATURE

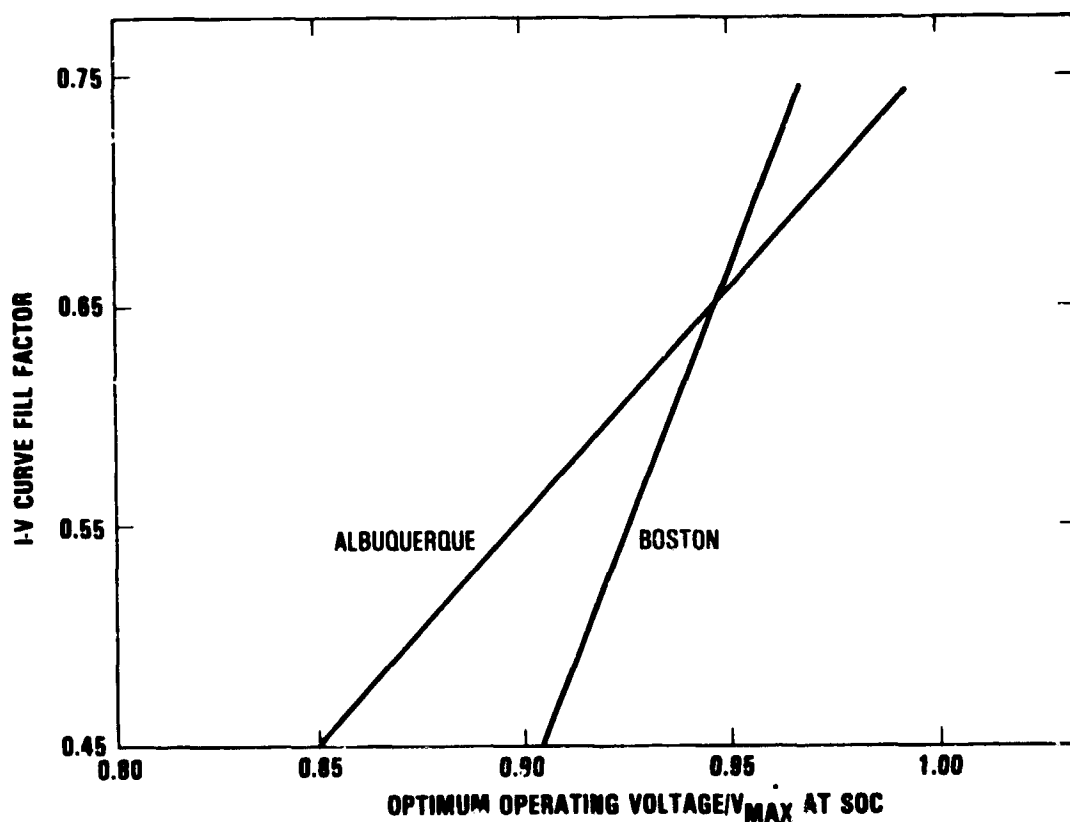
Array Optimum Operating Voltage vs Average
Daily Maximum Temperature



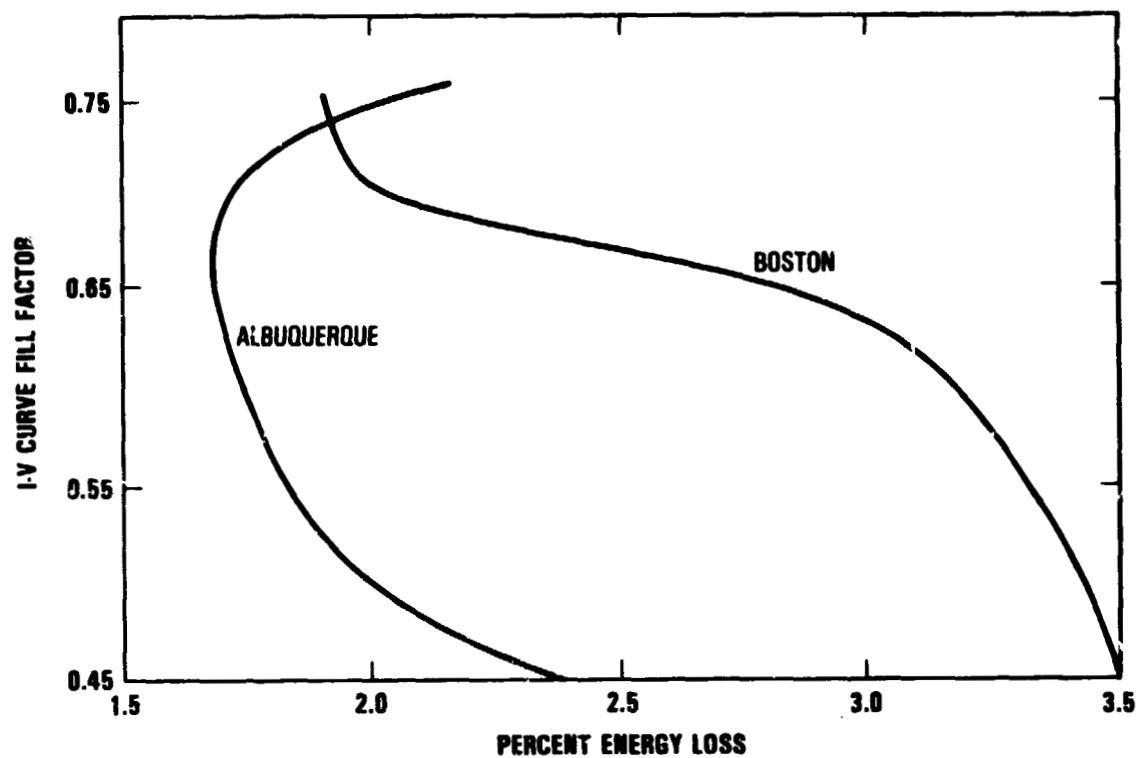
Array Annual Energy Loss With Fixed-Voltage Operation vs Standard Deviation of Daily Maximum Temperature



Optimum Operating Voltage vs Fill Factor

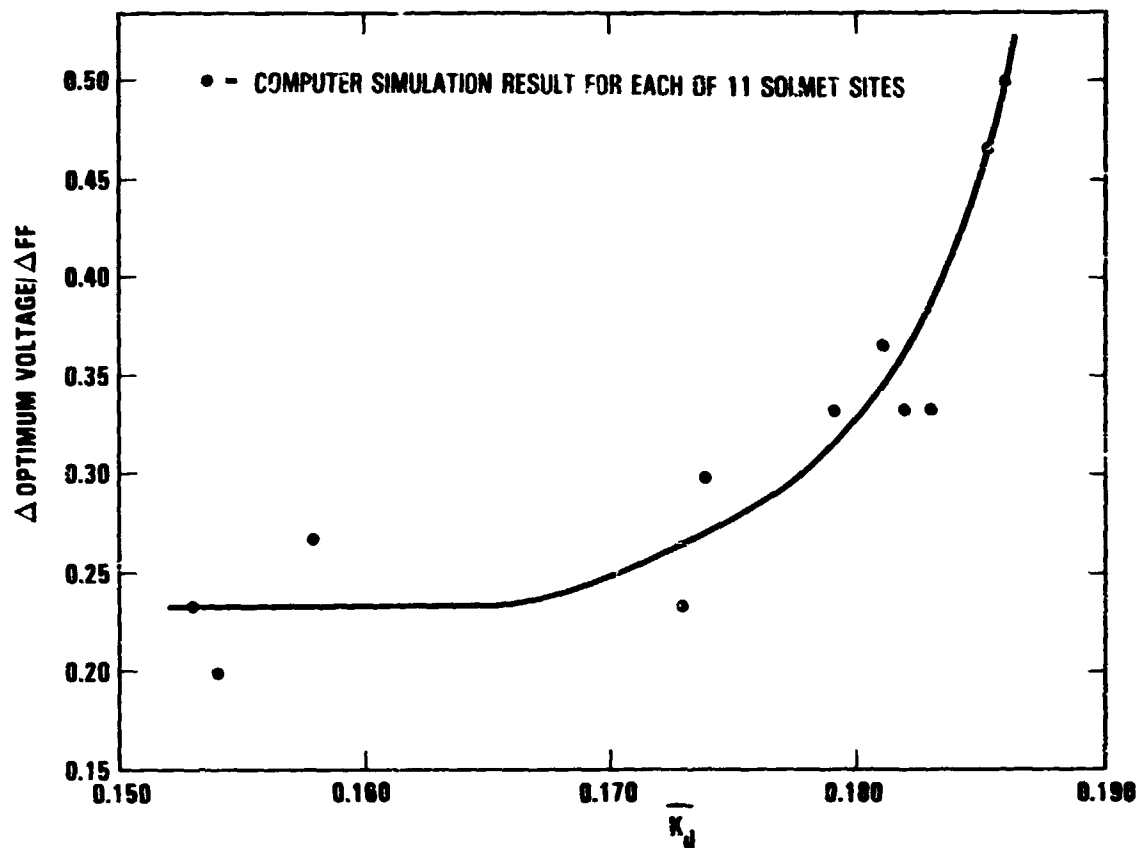


Percentage of Energy Loss vs Fill Factor



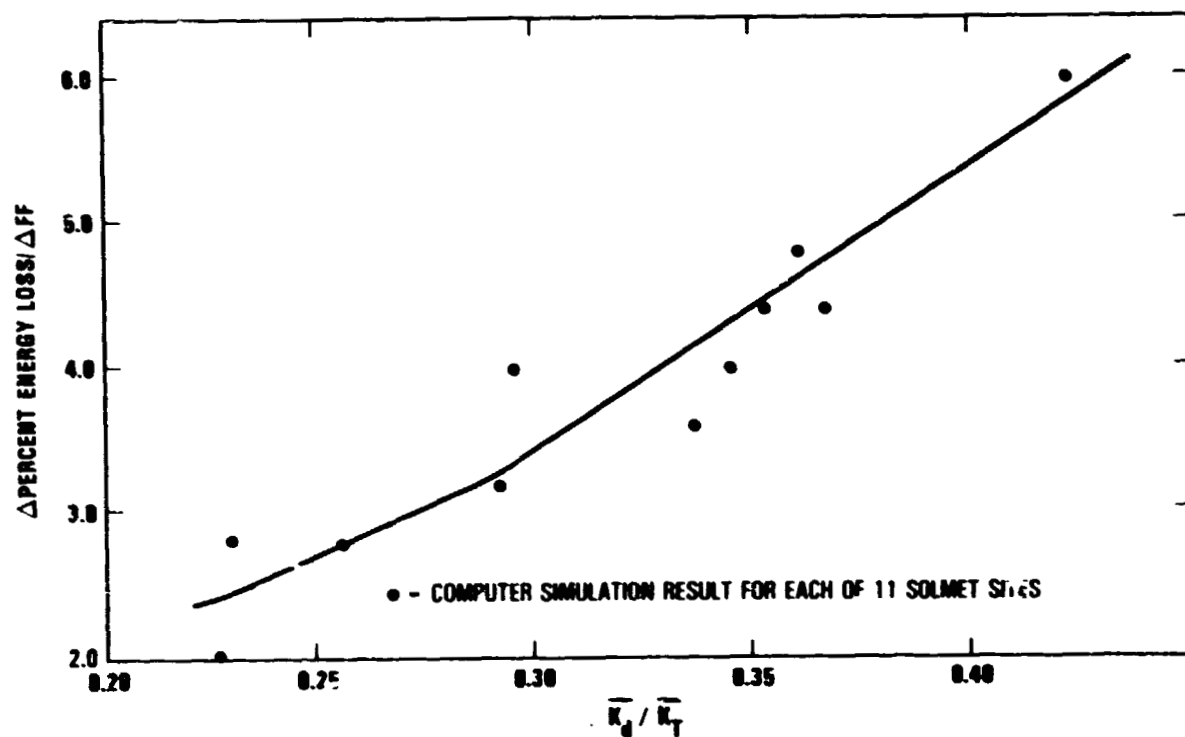
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Rate of Change of Optimum Voltage With Fill Factor vs \bar{K}_d

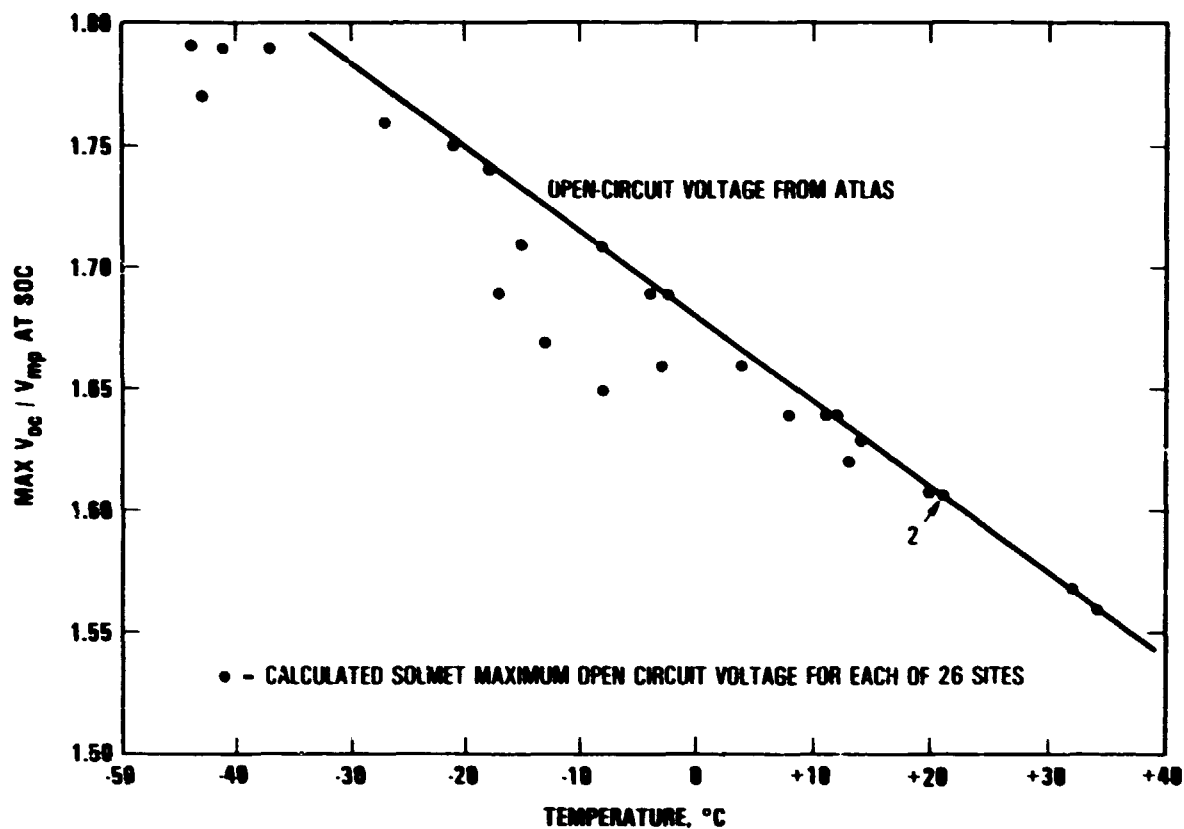


CONTROL OF FLOOR QUALITY

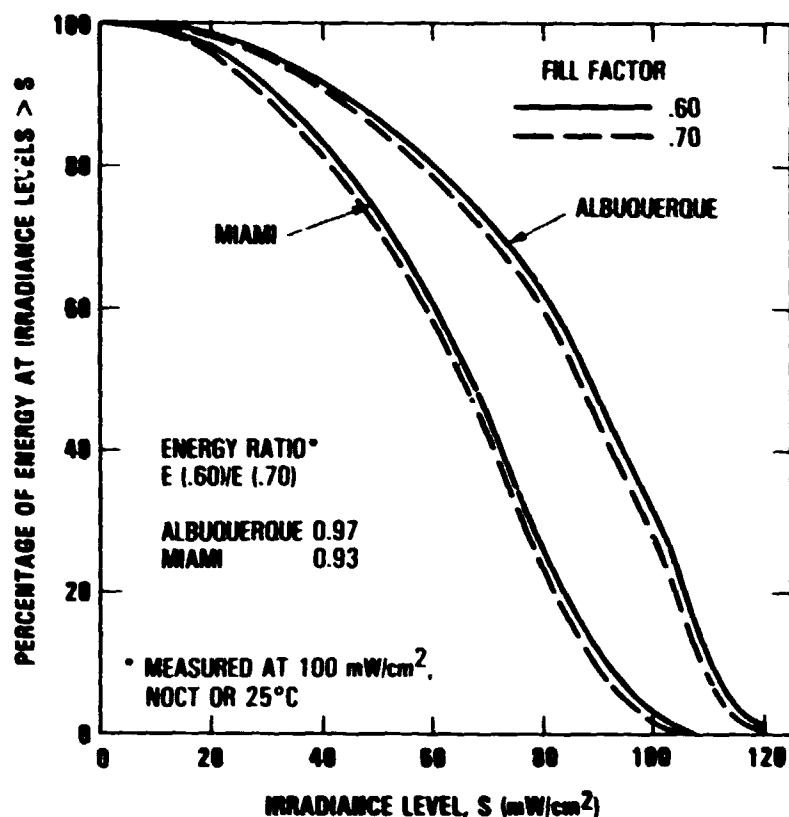
Rate of Change of Energy Loss With Fill Factor vs \bar{K}_d/\bar{K}_T



Maximum Open-Circuit Voltage (From SOLMET TMY)
vs Atlas Lowest Recorded Temperature



Array Energy Output vs Irradiance

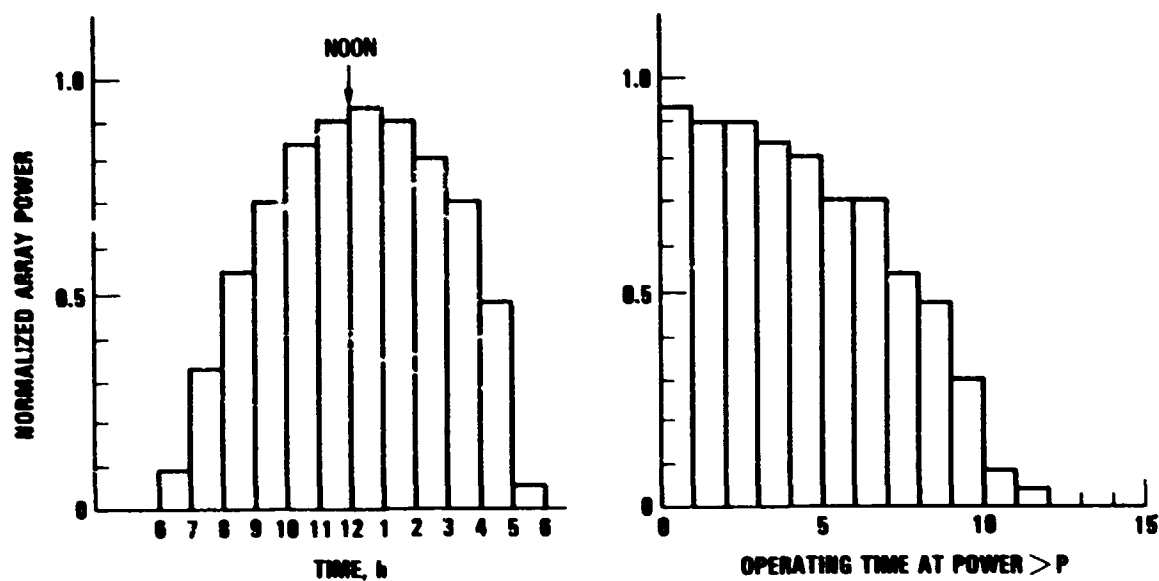


Comparison of Analysis Results With Variation in Array Tilt Angle

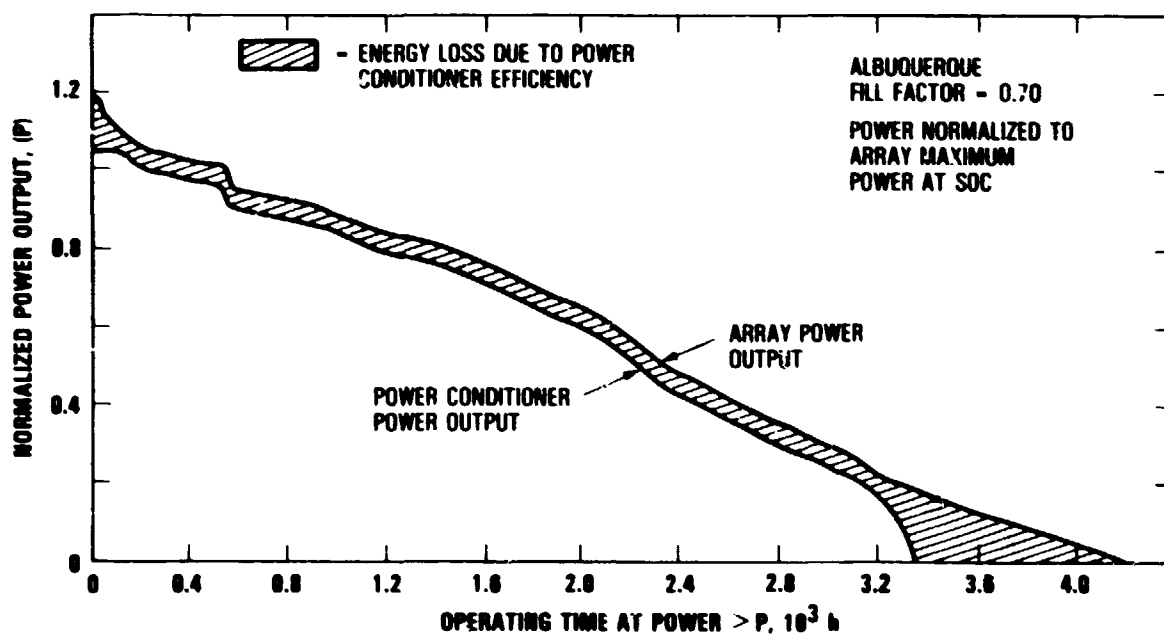
SITE	TILT ANGLE (DEGREES)	OPTIMUM OPERATING VOLTAGE	% ENERGY LOSS	\pm % VOLTAGE TRACKING WIDTH TO OBTAIN 0.1% LOSS	POWER LIMITS REQUIRED TO OBTAIN % ENERGY LOSS		CURRENT LIMITS REQUIRED TO OBTAIN % ENERGY LOSS	
					99.0	99.9	99.0	99.9
ALBUQUERQUE	35.05°	0.96	1.7	8.5	1.04	1.13	1.06	1.17
	20.05	0.95	1.7	8.5	1.01	1.11	1.04	1.15
	50.05	0.96	1.6	8.5	1.06	1.15	1.06	1.17
MIAMI	25.80°	0.93	0.7	5.5	0.82	0.91	0.86	0.97
	10.80	0.93	0.7	5.5	0.80	0.88	0.88	0.94
	40.80	0.93	0.7	6.0	0.83	0.93	0.87	0.98
BISMARCK	46.77°	0.97	2.5	12.5	0.96	1.08	0.95	1.05
	31.77	0.97	2.4	12.5	0.94	1.06	0.96	1.05
	61.77	0.98	2.7	13.0	0.95	1.10	0.93	1.04

* TILT ANGLE EQUALS SITE LATITUDE

Normalized Power vs Operating Time



Effect of Power Conditioner Efficiency on Array Annual Power Production



Fraction of Annual Array Energy Available
in Various Relative Power Intervals

SITE	ARRAY RELATIVE POWER INTERVAL					
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2
ALBUQUERQUE NM	0.0343	0.0782	0.1040	0.2133	0.3693	0.2010
BISMARCK ND	0.0750	0.1363	0.1442	0.2435	0.3277	0.0739
BOSTON MA	0.0907	0.1383	0.1965	0.2840	0.2741	0.0163
BROWNSVILLE TX	0.0572	0.1393	0.2025	0.3967	0.1985	0.0138
CARIBOU ME	0.0779	0.1734	0.1754	0.2511	0.2542	0.0689
CHARLESTON SC	0.0541	0.1512	0.1998	0.3749	0.2043	0.0158
FORT WORTH TX	0.0590	0.1185	0.1642	0.3184	0.2995	0.0403
FRESNO CA	0.0446	0.0990	0.1213	0.2721	0.4098	0.0533
MIAMI FL	0.0508	0.1554	0.2382	0.4448	0.1073	0.0035
OMAHA NB	0.0682	0.1282	0.1428	0.2723	0.3119	0.0767
PHOENIX AZ	0.0339	0.0679	0.1275	0.3091	0.3821	0.0596
SEATTLE WA	0.1302	0.1603	0.1847	0.2524	0.2692	0.0032
AVERAGE	0.0847	0.1305	0.1667	0.3027	0.2833	0.0522
CUMULATIVE VALUE OF AVERAGES	0.0847	0.1952	0.3619	0.6646	0.9479	1.0000

Summary and Conclusions

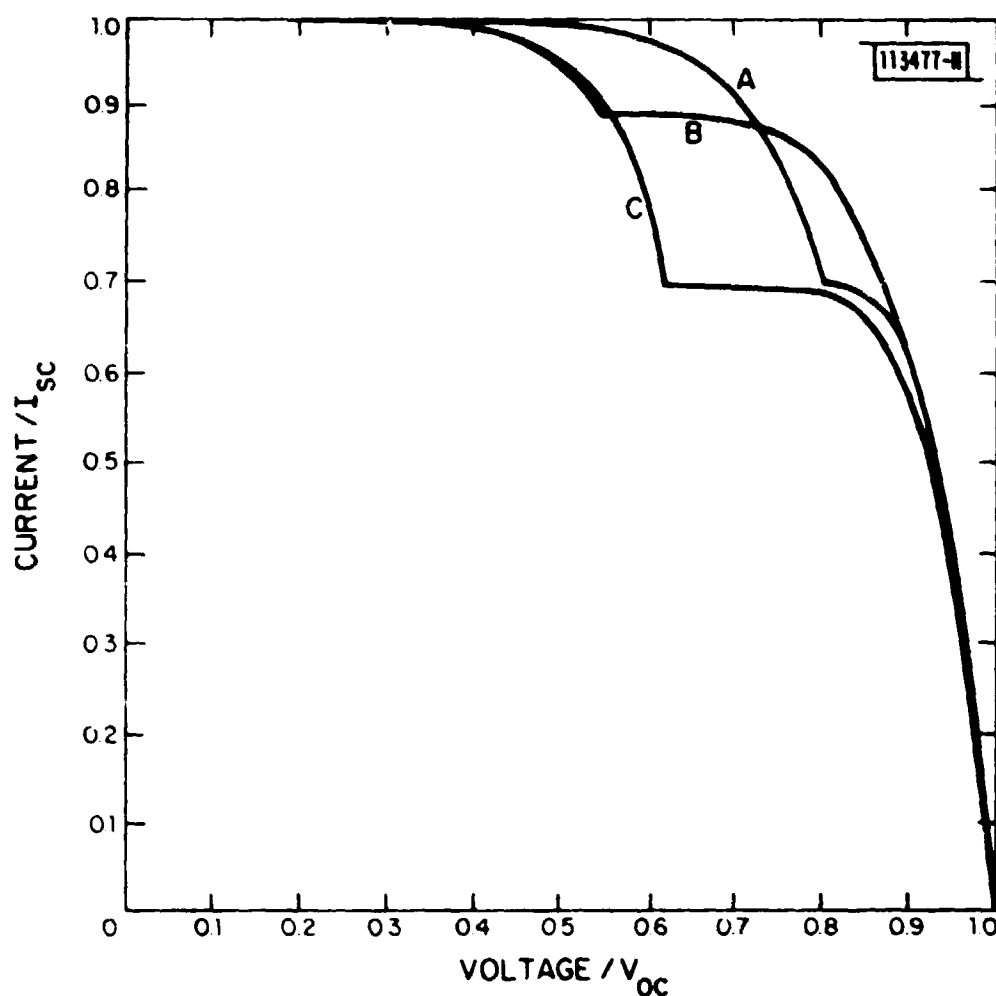
- EXCELLENT CORRELATIONS OBTAINED WITH RECORDED WEATHER DATA FOR FOLLOWING:
 - ARRAY OPTIMUM OPERATING VOLTAGE
 - ANNUAL ENERGY LOSS (%)
 - VARIATION OF OPTIMUM OPERATING VOLTAGE AND ENERGY LOSS (%) WITH FILL FACTOR
 - MAXIMUM OPEN-CIRCUIT VOLTAGE
- SENSITIVITY OF ANALYSIS RESULTS TO ARRAY TILT ANGLE IS MINOR
- DETERMINED COMPOSITE ENERGY FRACTION PER GIVEN POWER INTERVAL FROM DATA FOR 26 SITES

ARRAY DEGRADATION AND VOLTAGE CONTROL STRATEGIES

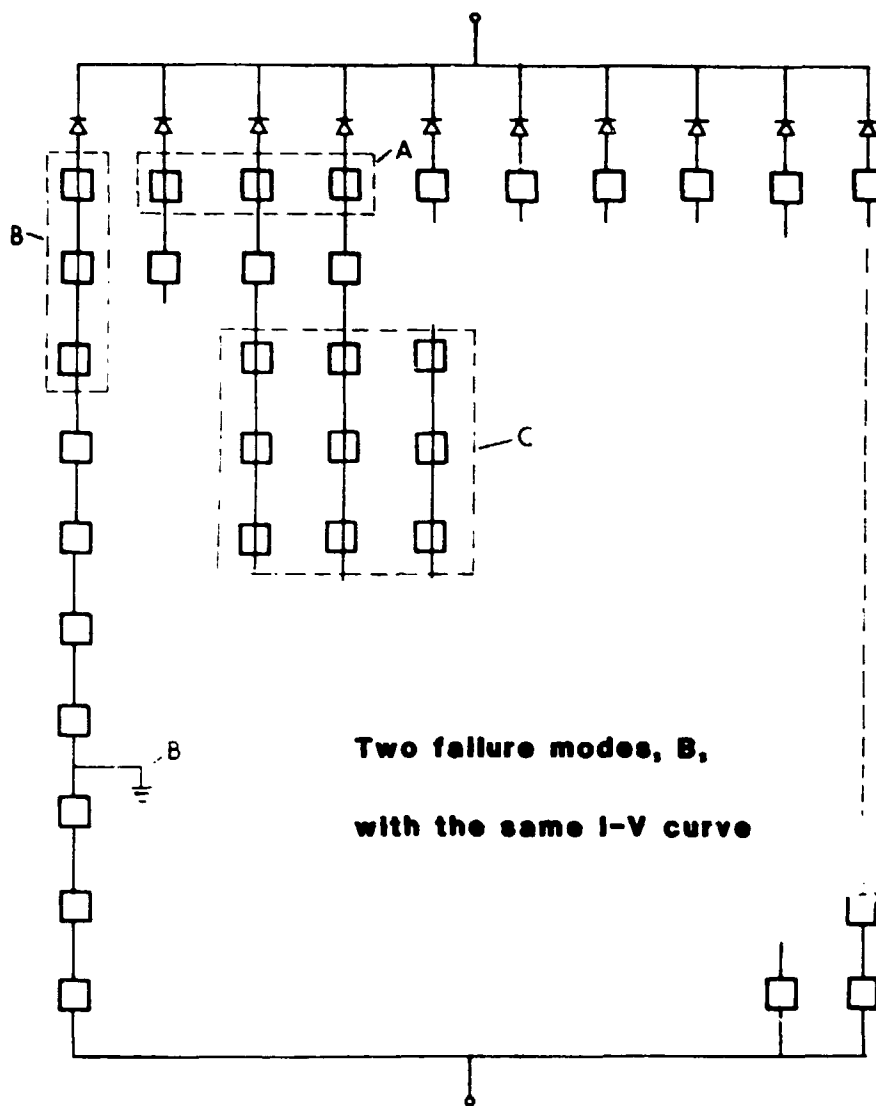
MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

H.M. Branz
G.W. Hart
C.H. Cox

Typical Single "Glitch-Point" Curves



Shorts in a Series-Wired Array



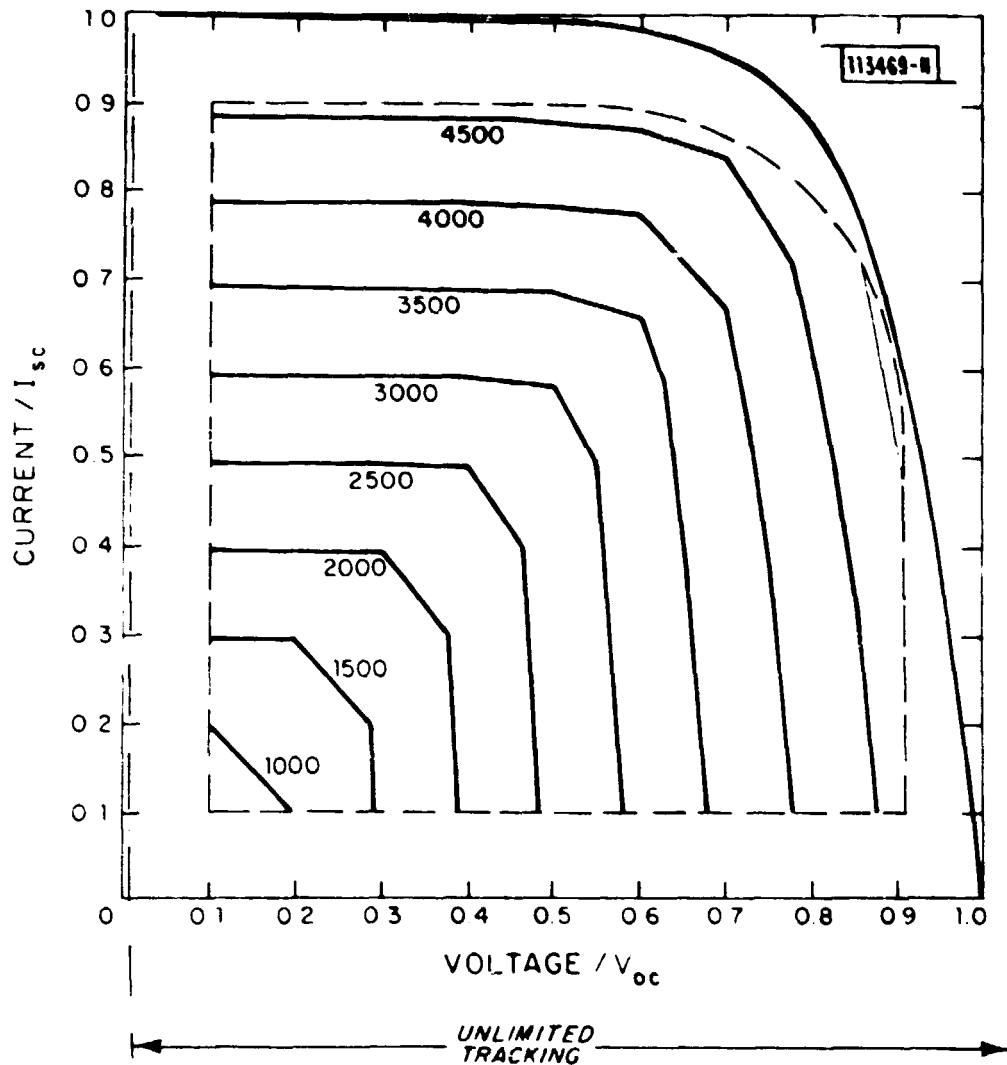
**Two failure modes, B,
with the same I-V curve**

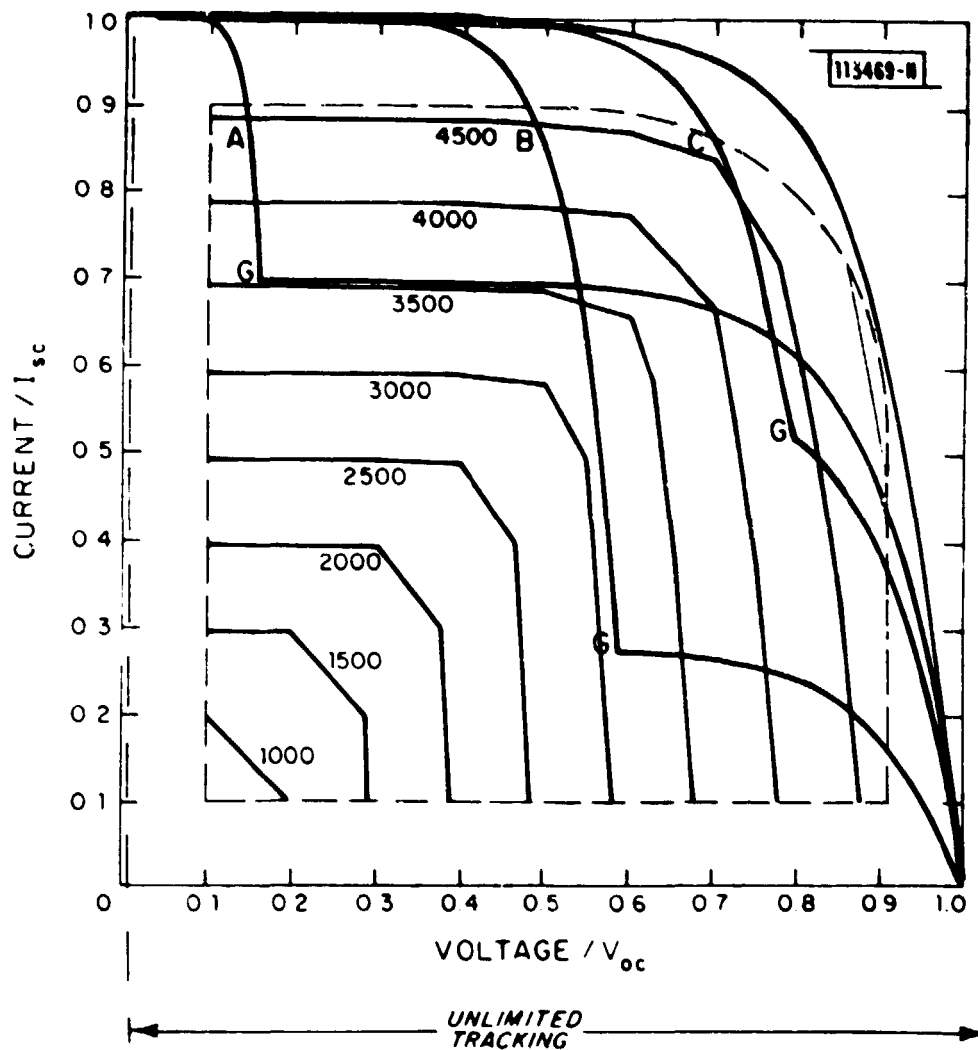
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Method

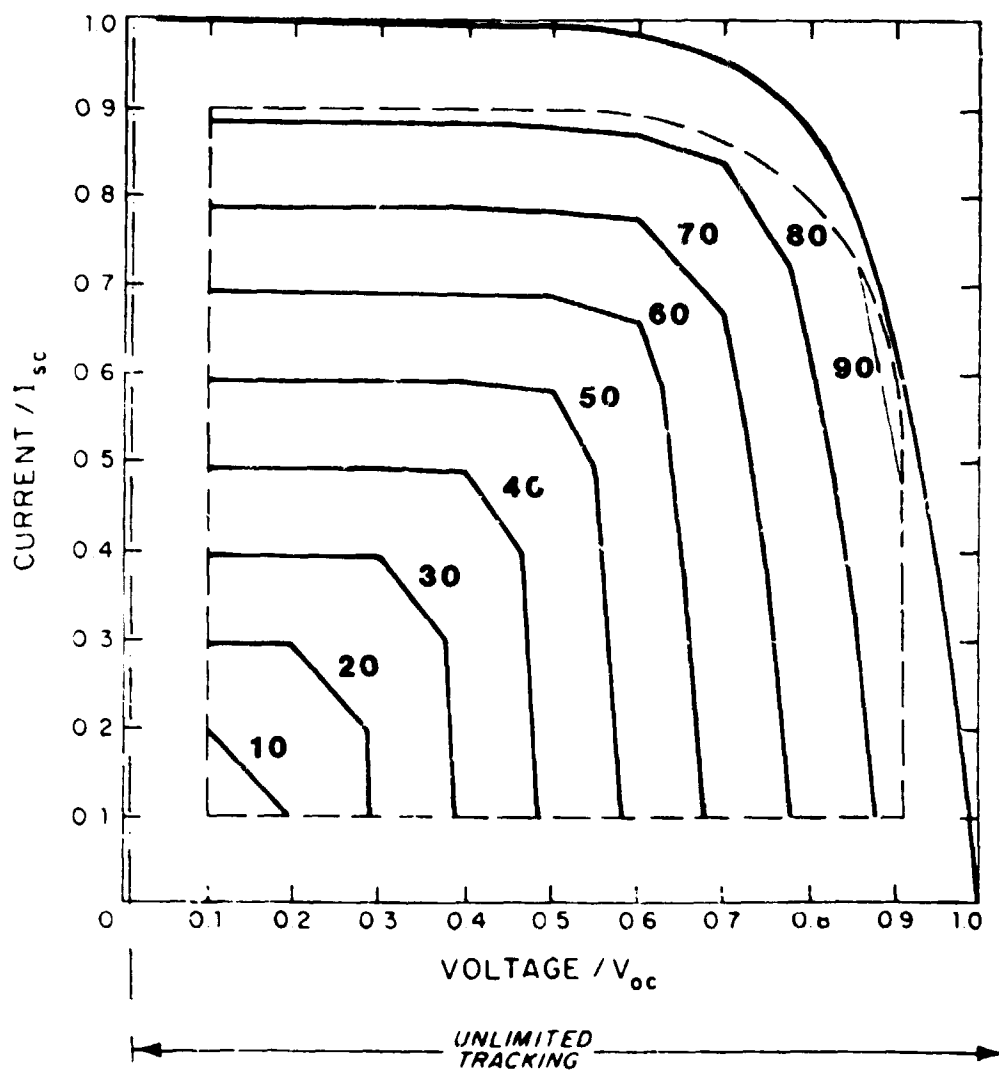
- o Focus on resulting curve shape;
not on underlying failure**
- o Assume single "glitch-point" curves**
- o Simulate using TMY hourly data**
- o Compare annual energy between ideal
maximum power tracker and best fixed
voltage**

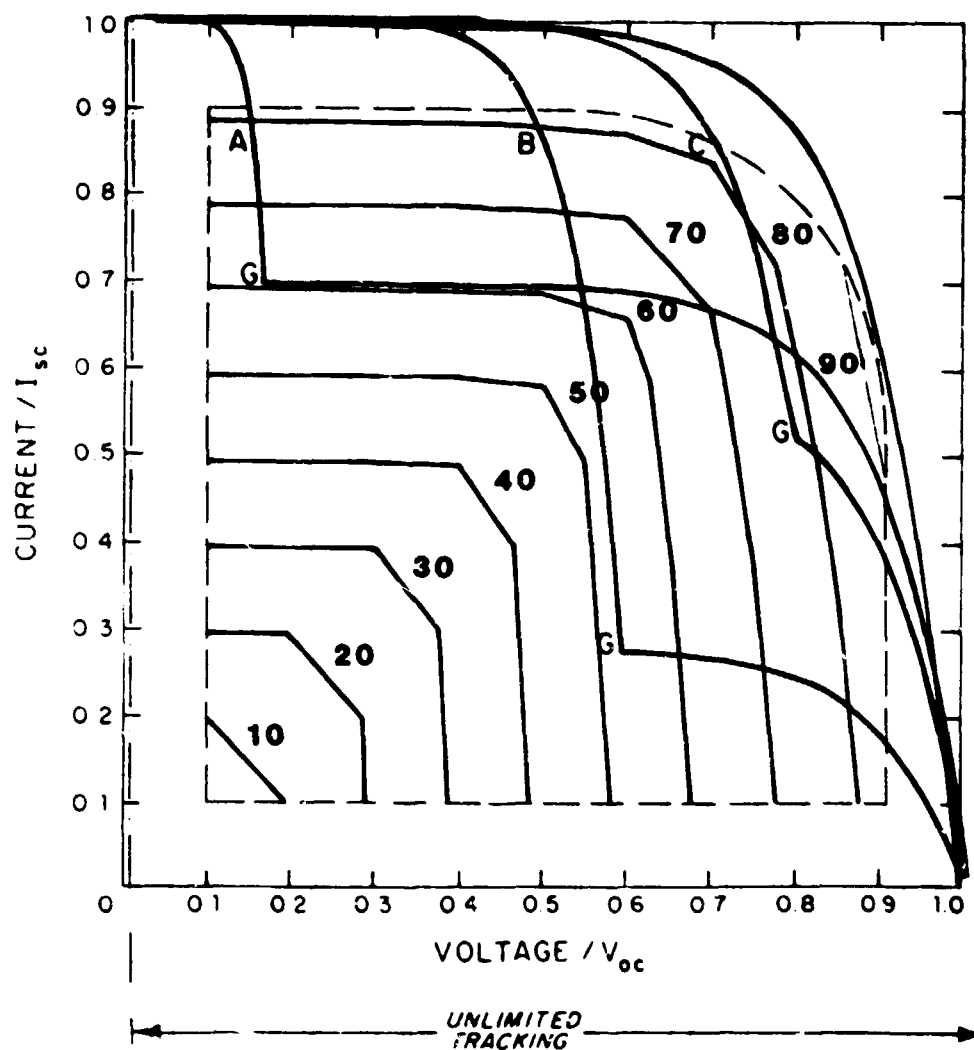
MPT Array Energy as a Function of Glitch-Point Location



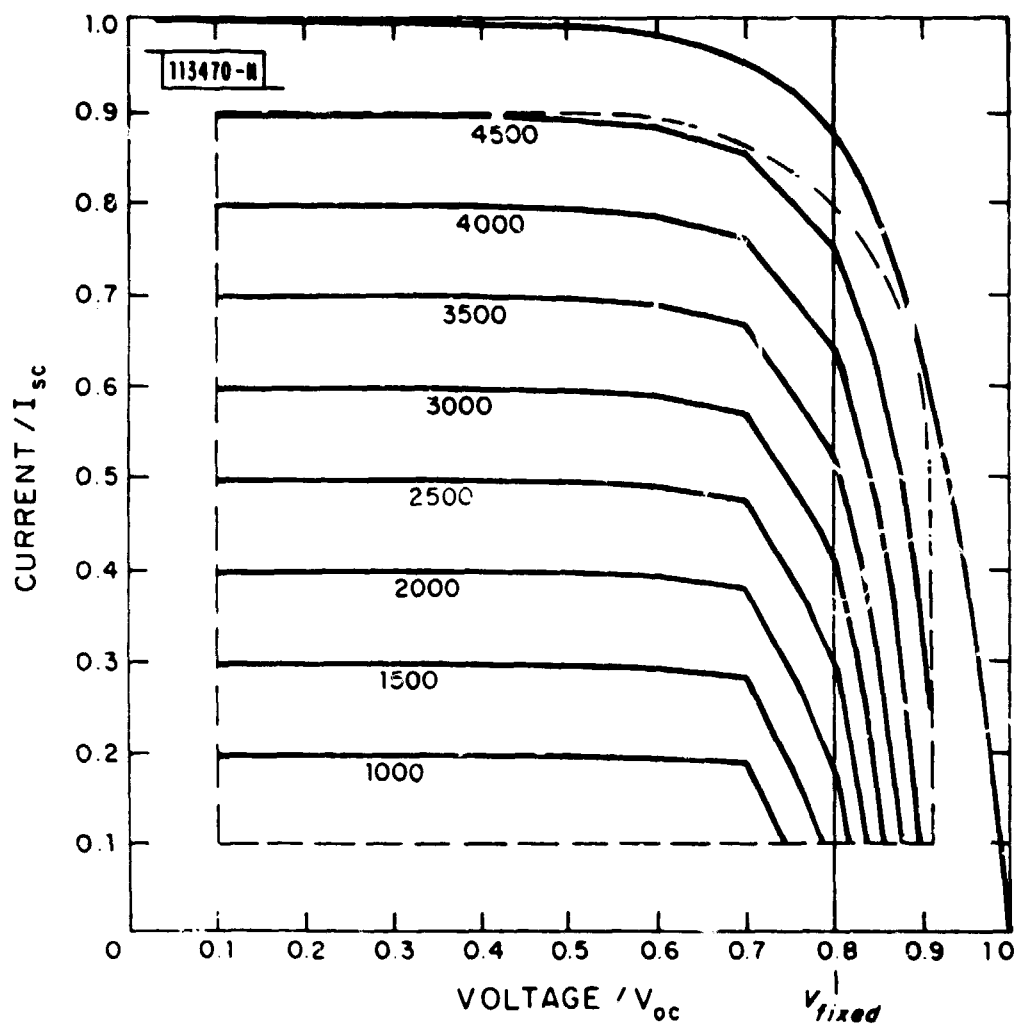


Percentage of MPT Array Energy vs Glitch-Point Location

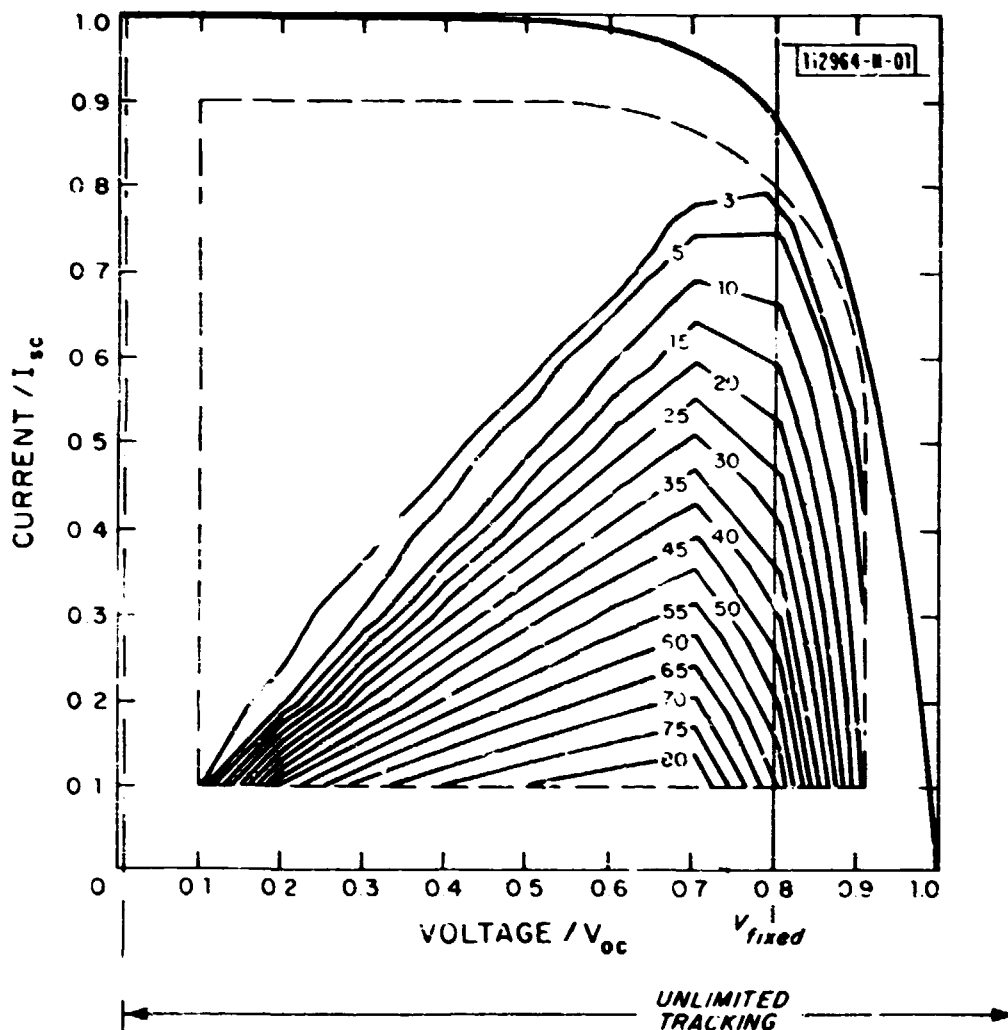




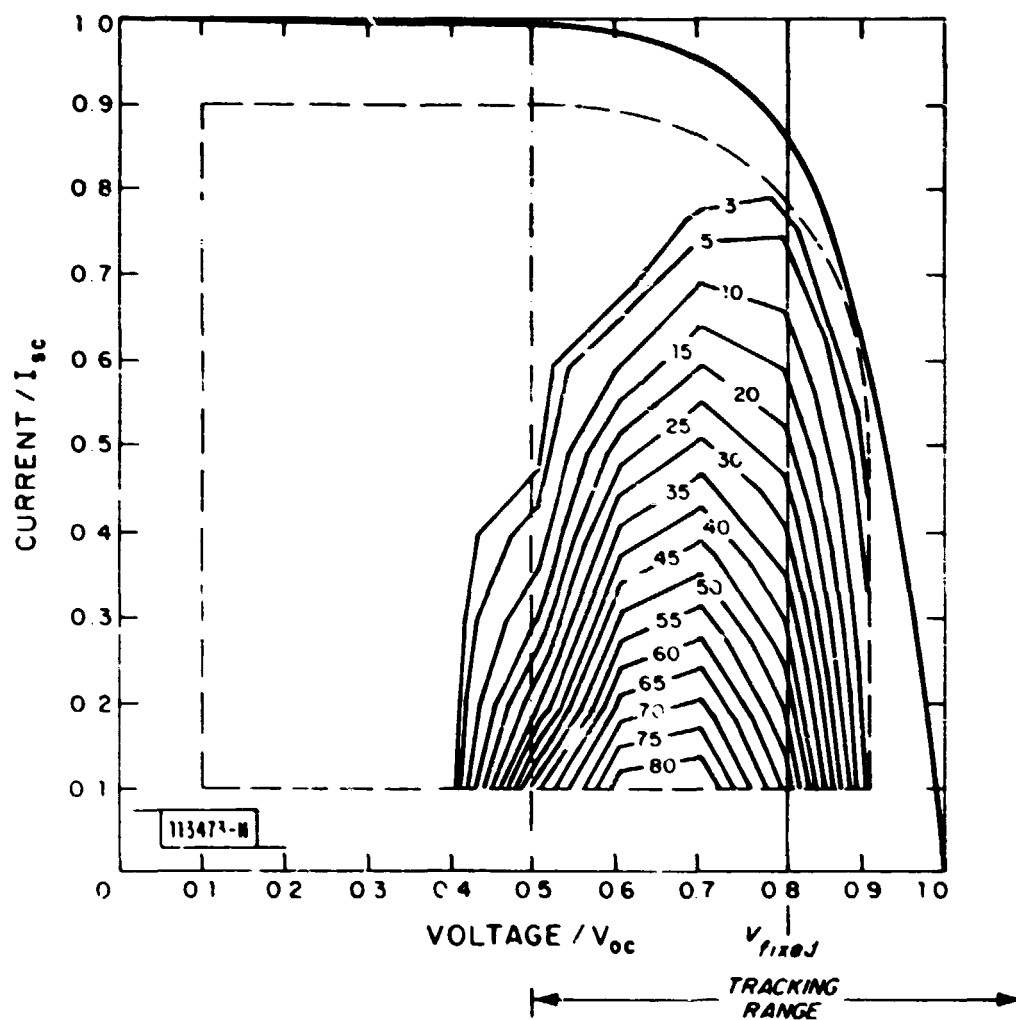
BFV Array Energy as a Function of Glitch-Point Location

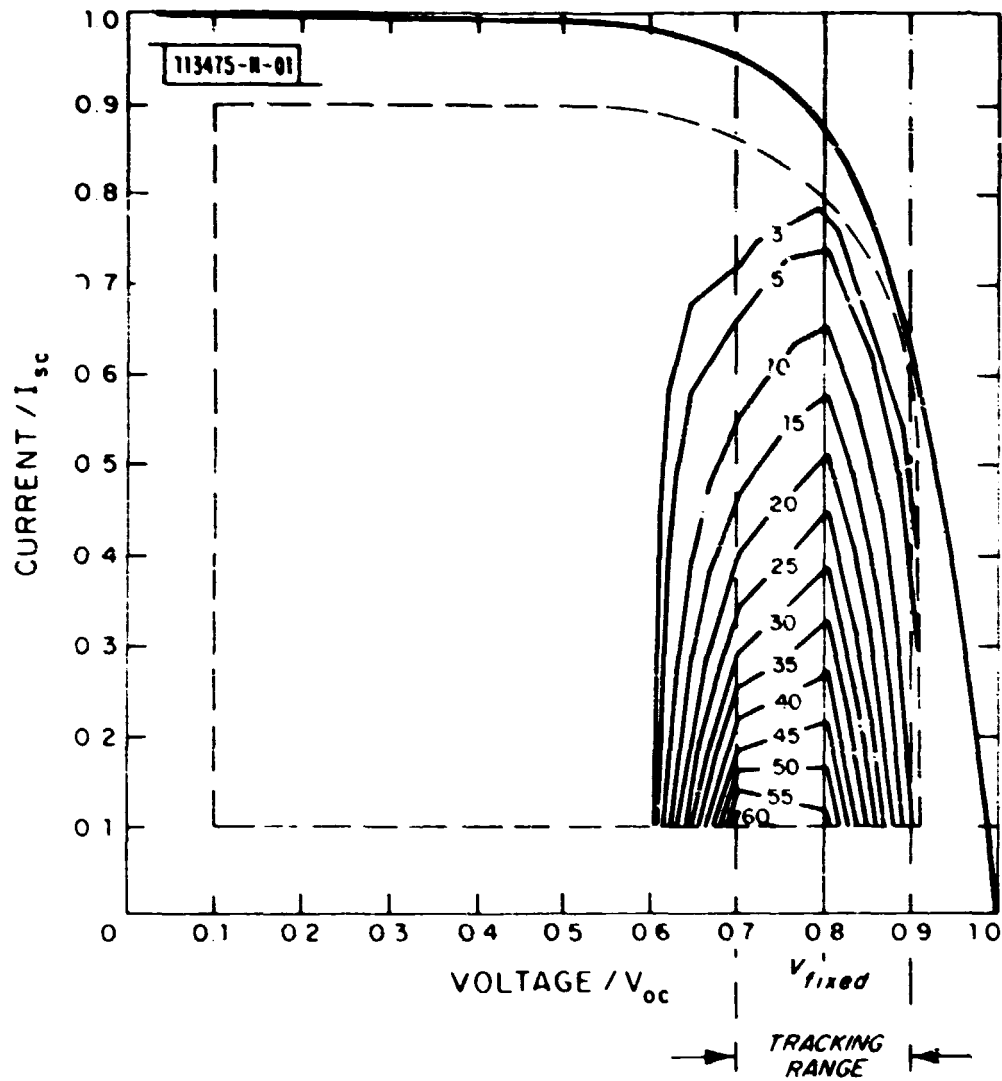


BFV Losses Relative to Full-Range MPT



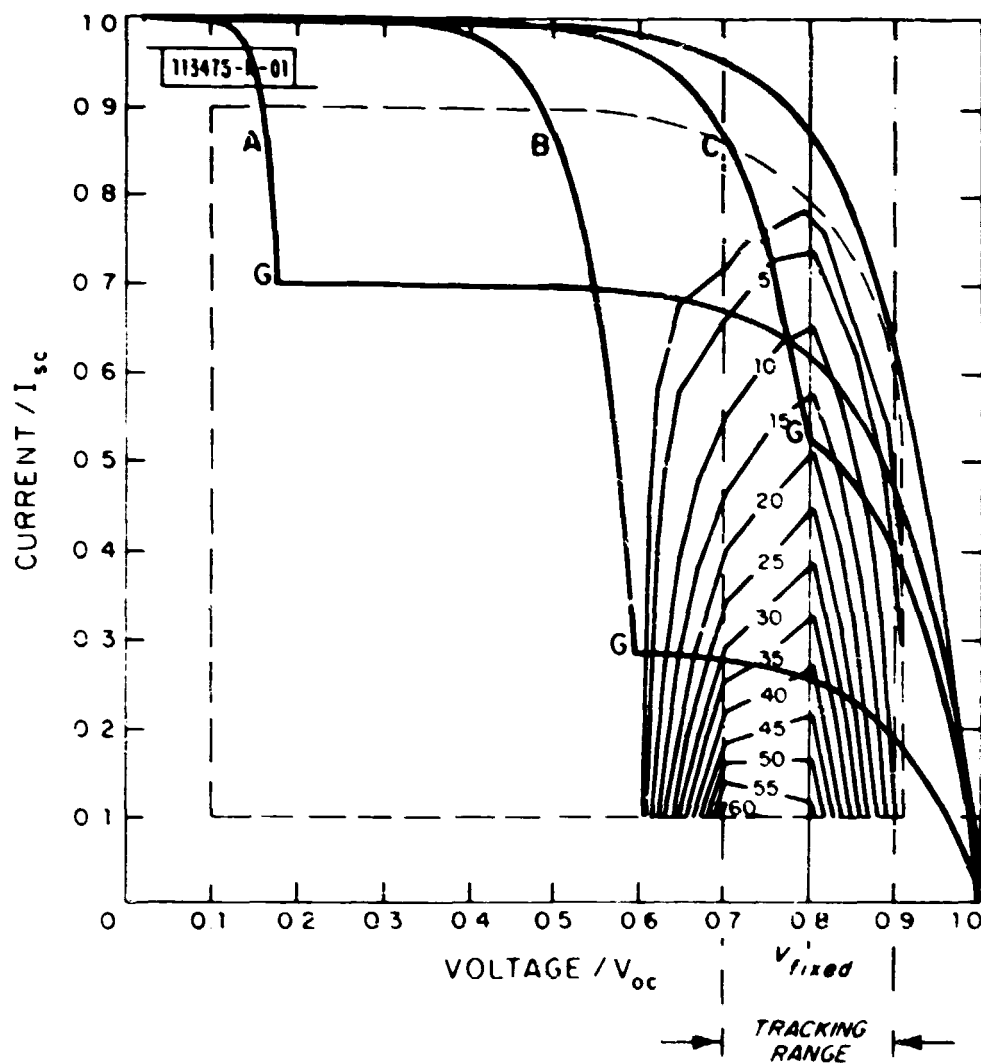
BFV Losses Relative to Limited-Range MPT



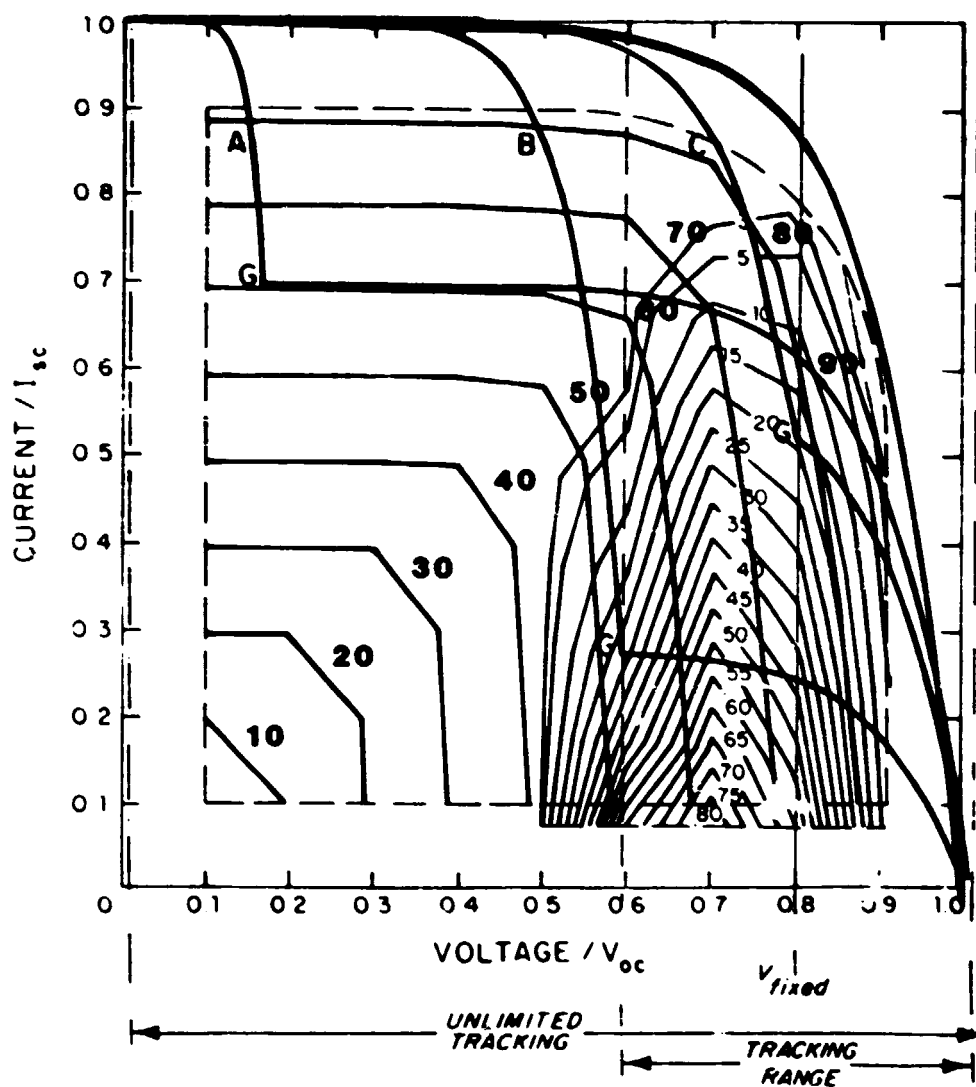


ENGINEERING SCIENCES AREA
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

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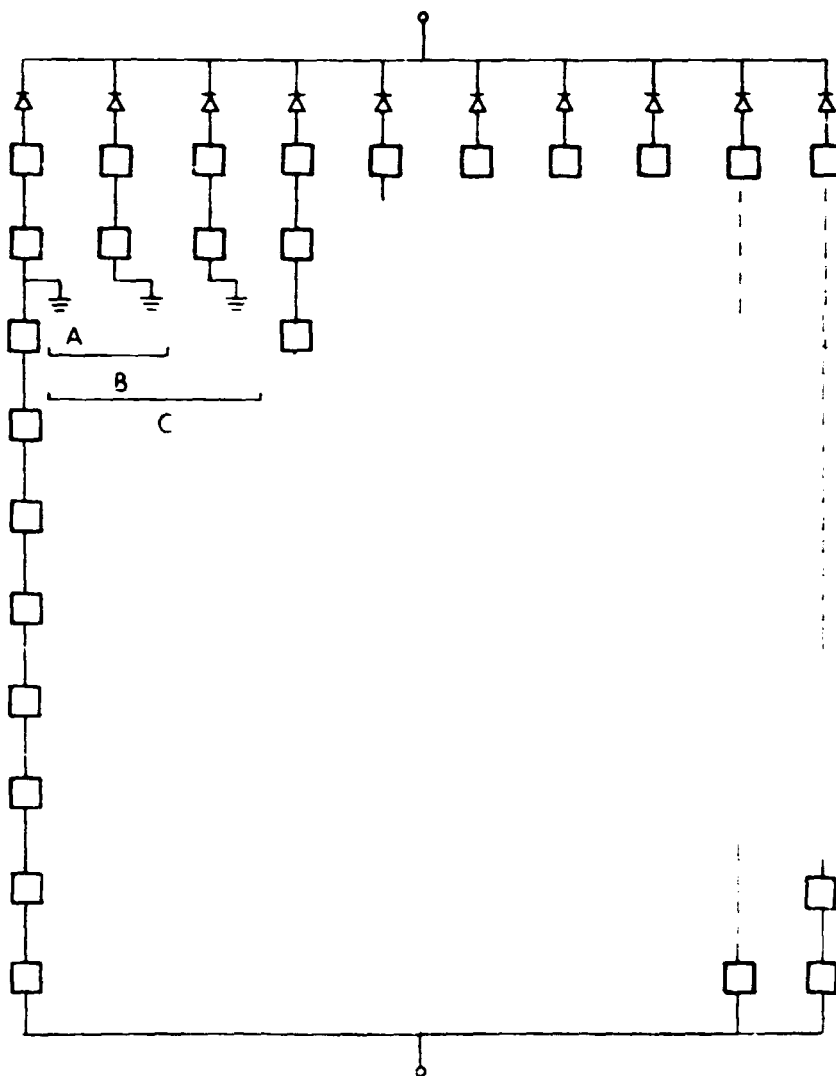


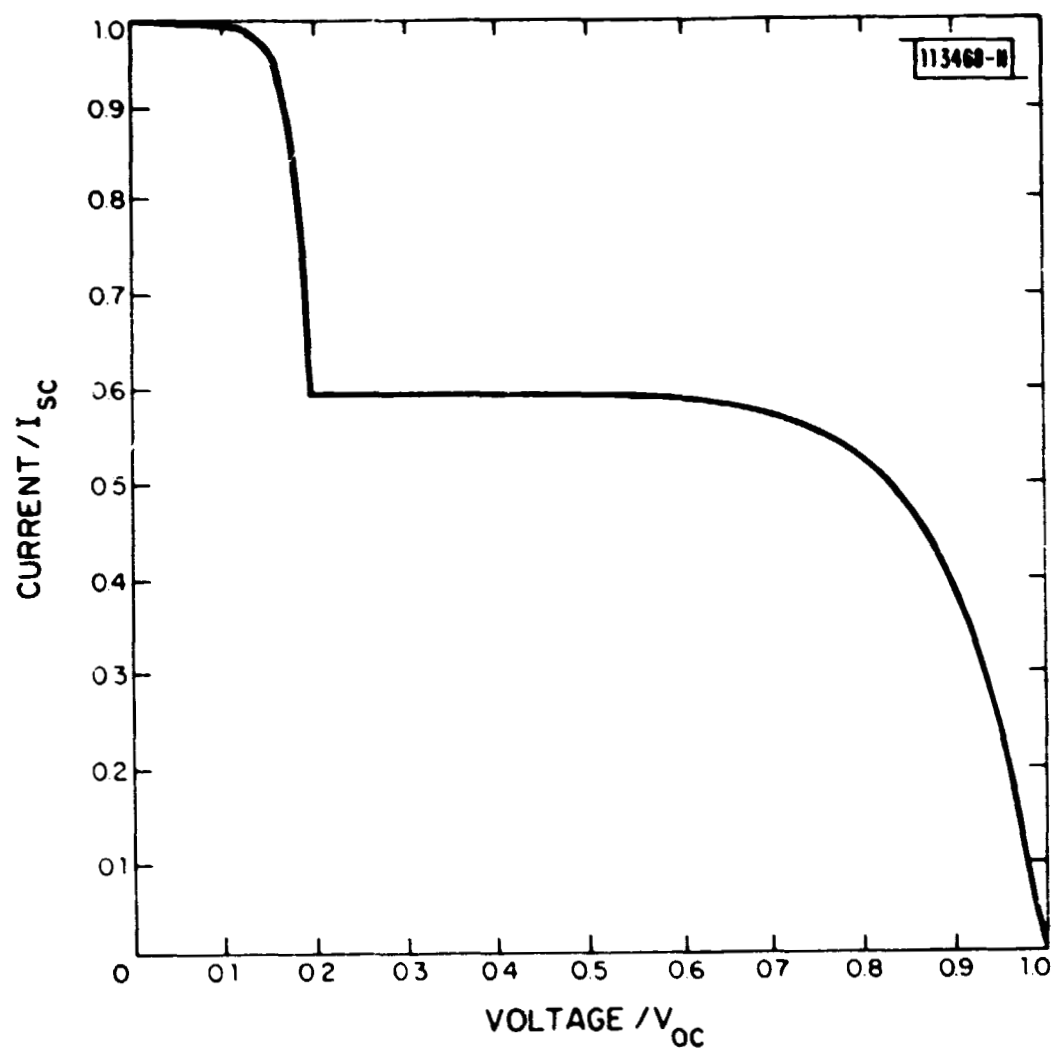
Percent of MPT Array Energy vs Glitch-Point Location

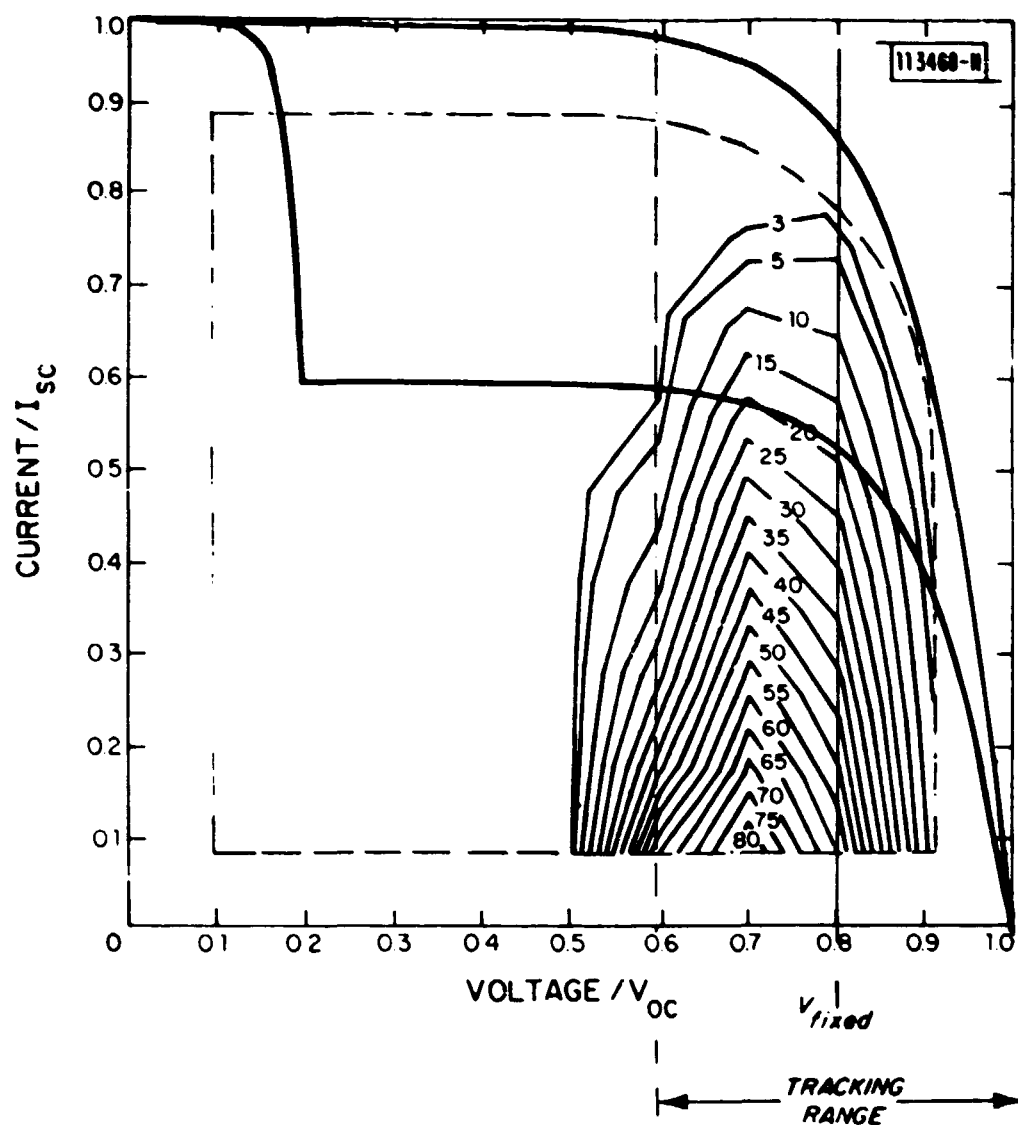


Shorts to Ground in a Series-Wired Array

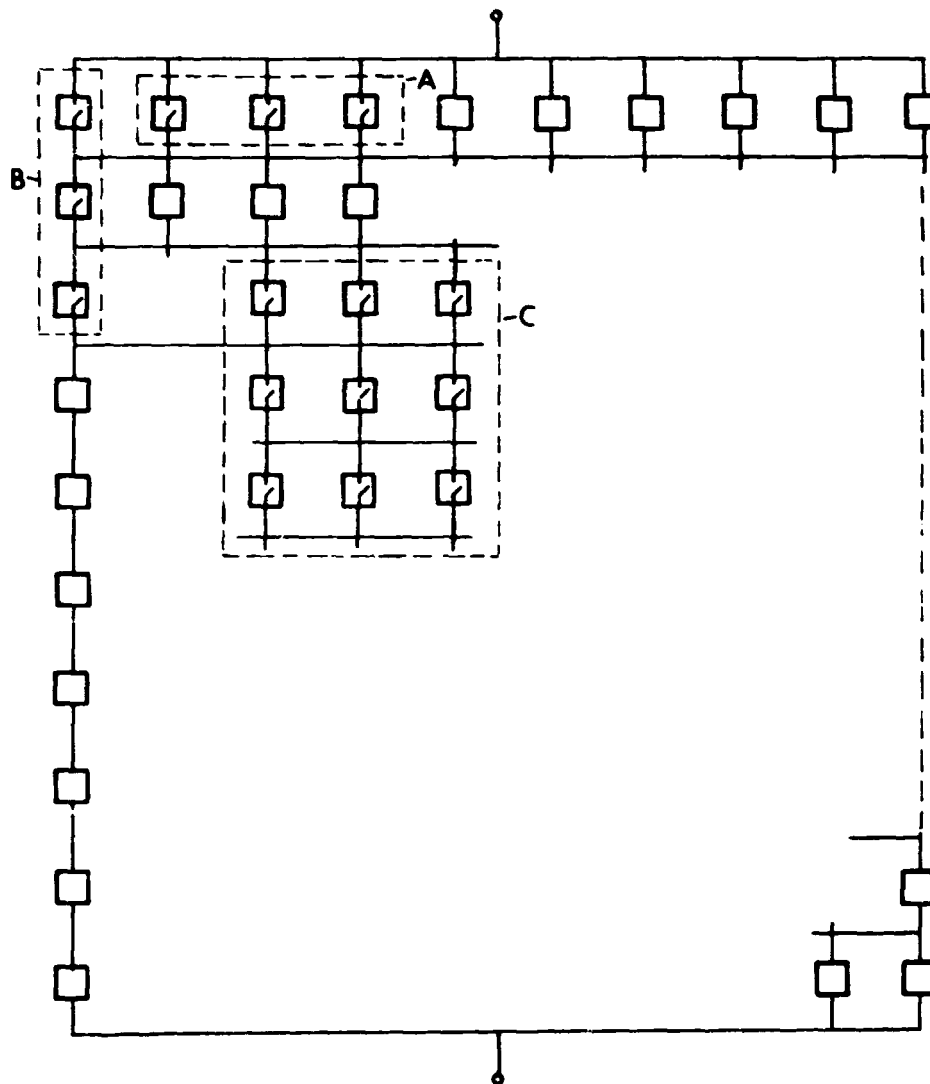
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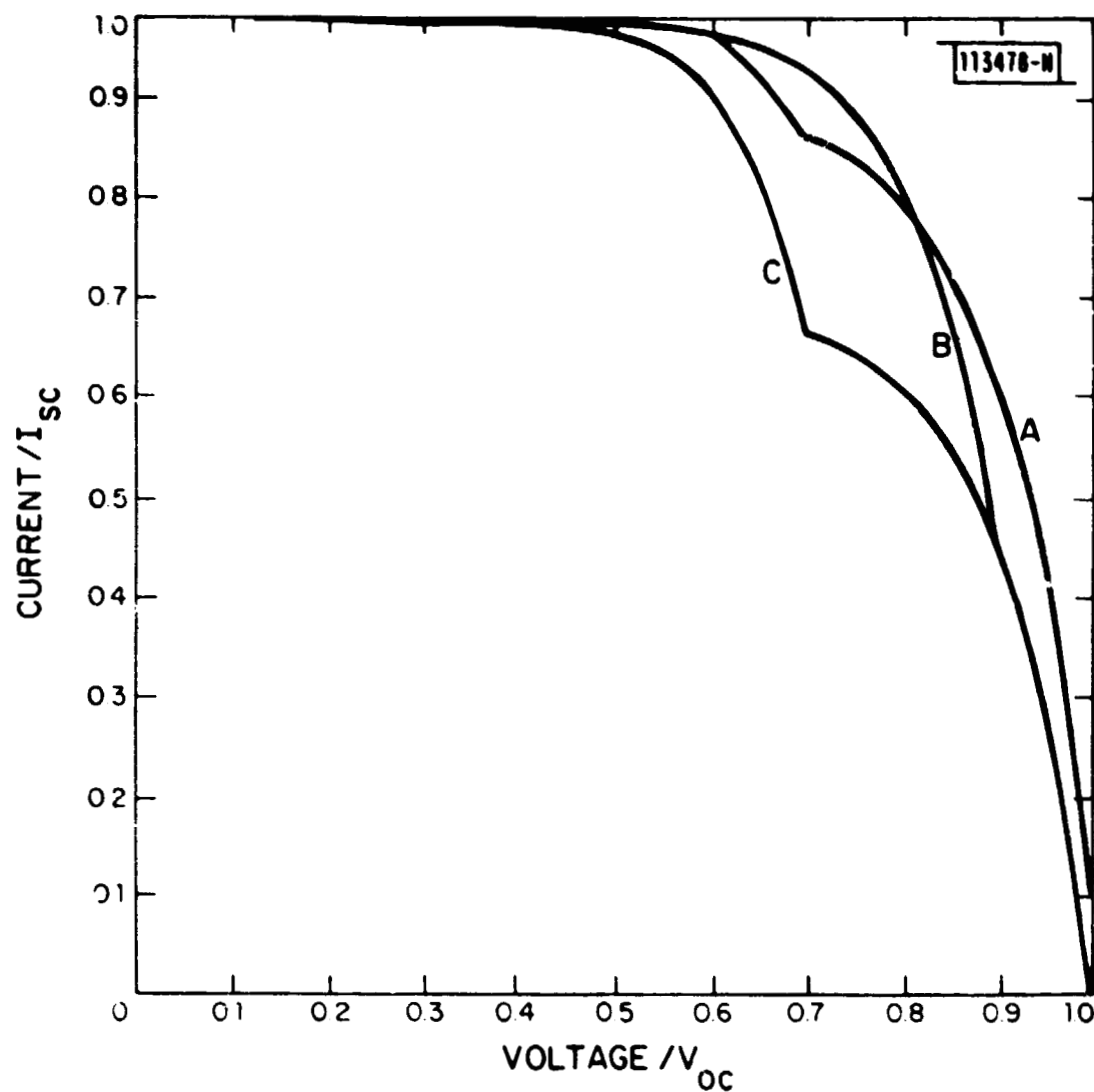






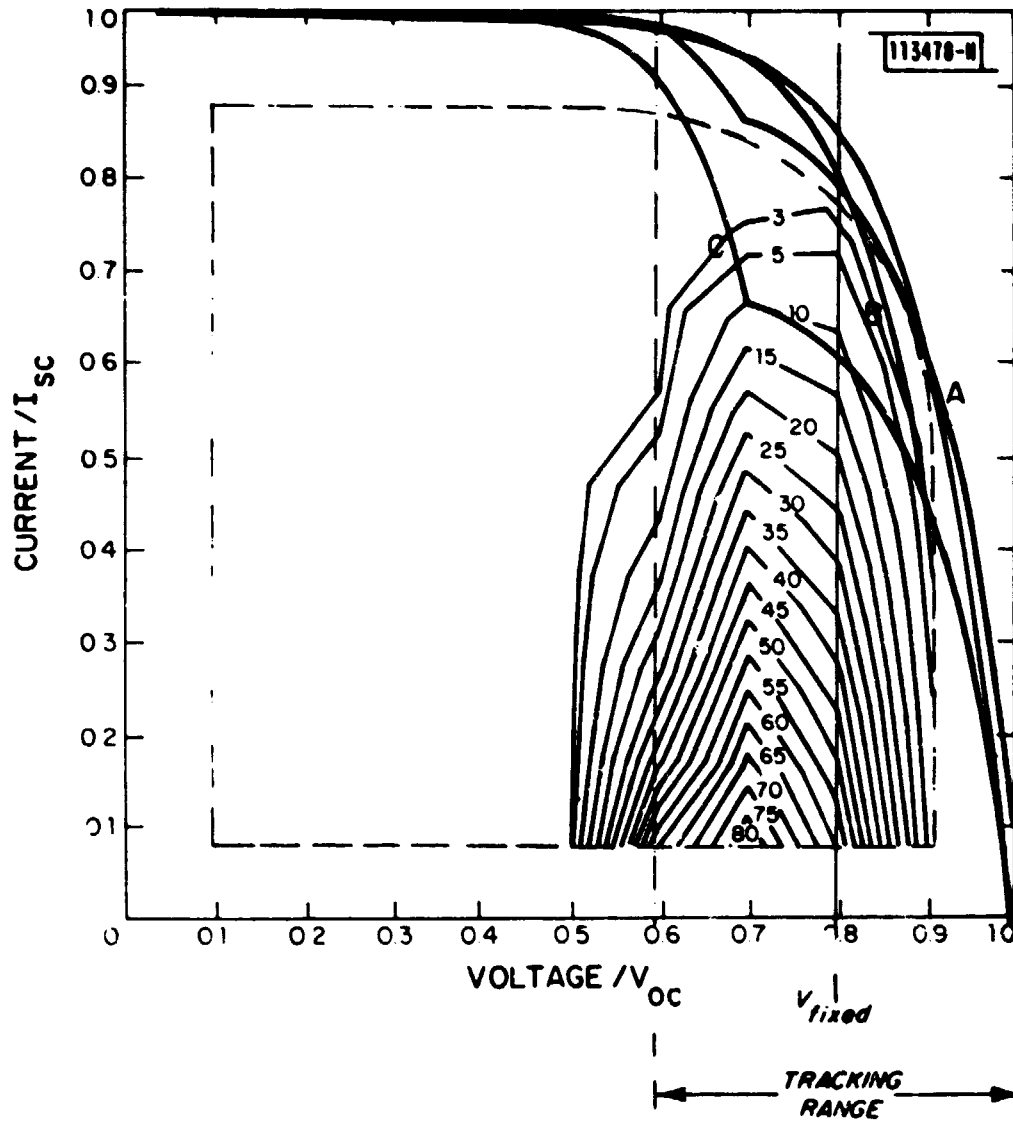
Opens in a Parallel-Wired Array



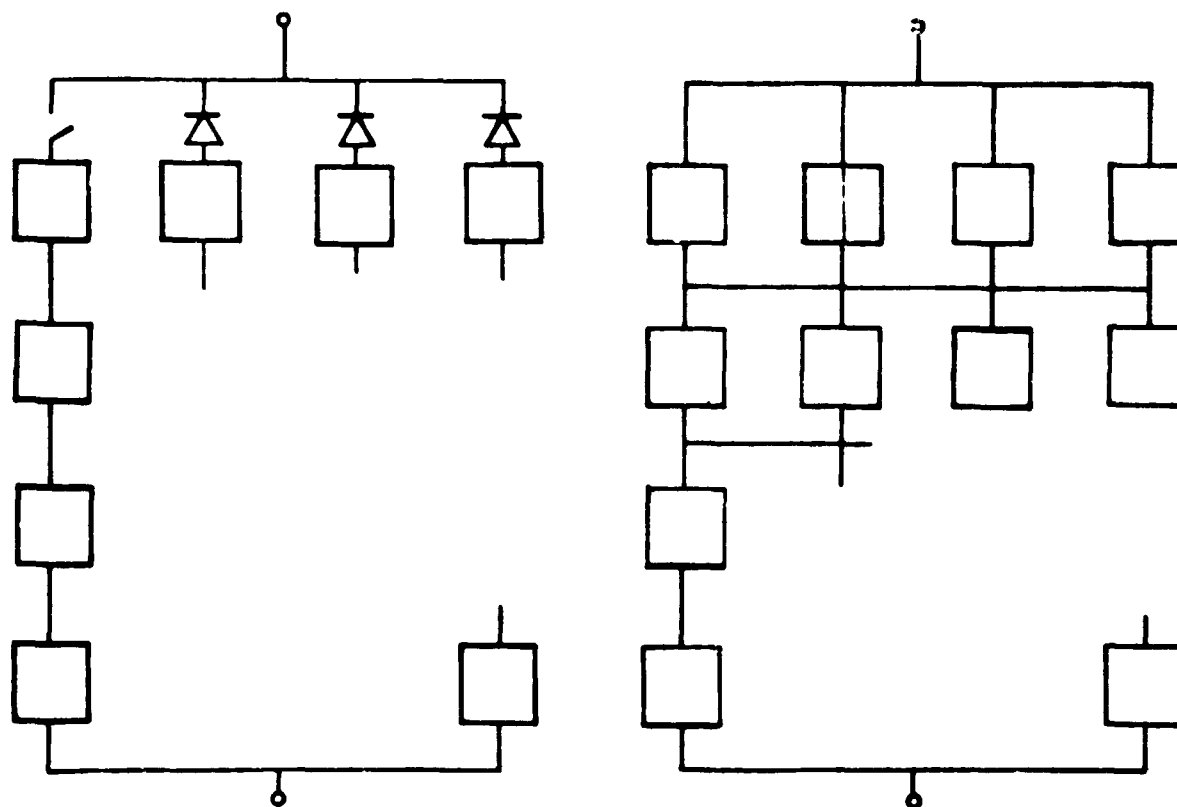


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Two Special Cases



Conclusions

Best Fixed Voltage vs Ideal Maximum Power Tracker

Small Difference

- o Open in series connected array
- o Short to ground near top of array

Large Difference

- o Short in parallel connected array
- o Glitch below maximum power radial

I-V CURVE DATA BASE AND APPLICATIONS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY LINCOLN LABORATORY

G.W. Hart
H.M. Branz
C.H. Cox

Data Base

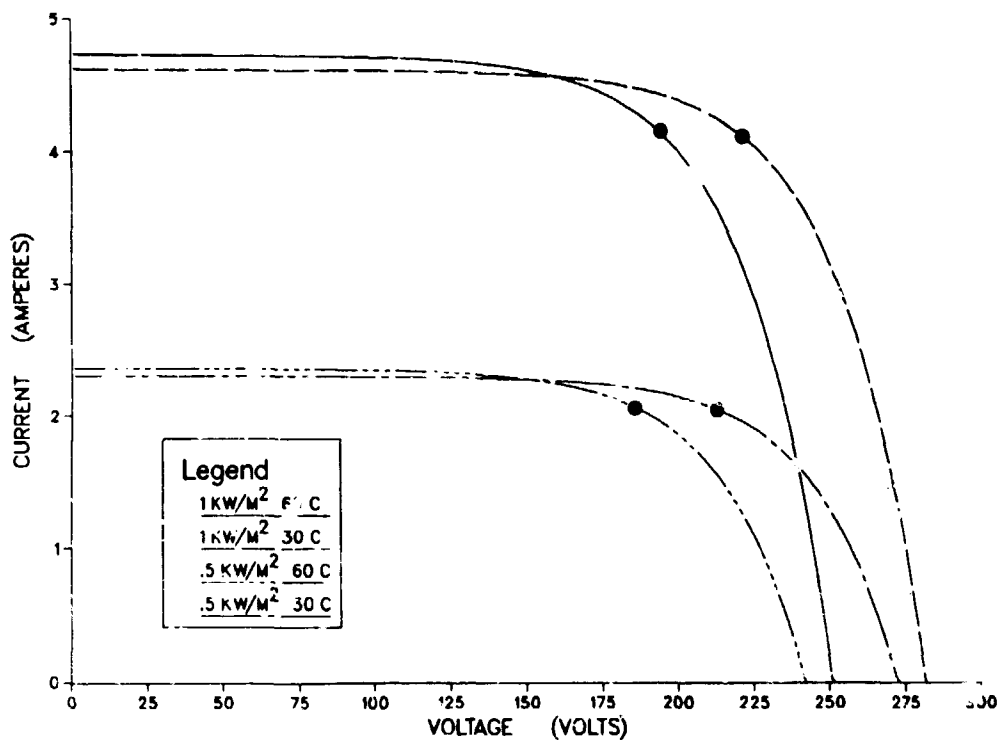
- IV CURVES EVERY 3 MINUTES
- COLLATERAL DATA
 - CELL TEMPERATURE
 - WEATHER CONDITIONS
 - PILOT CELL DATA

Applications

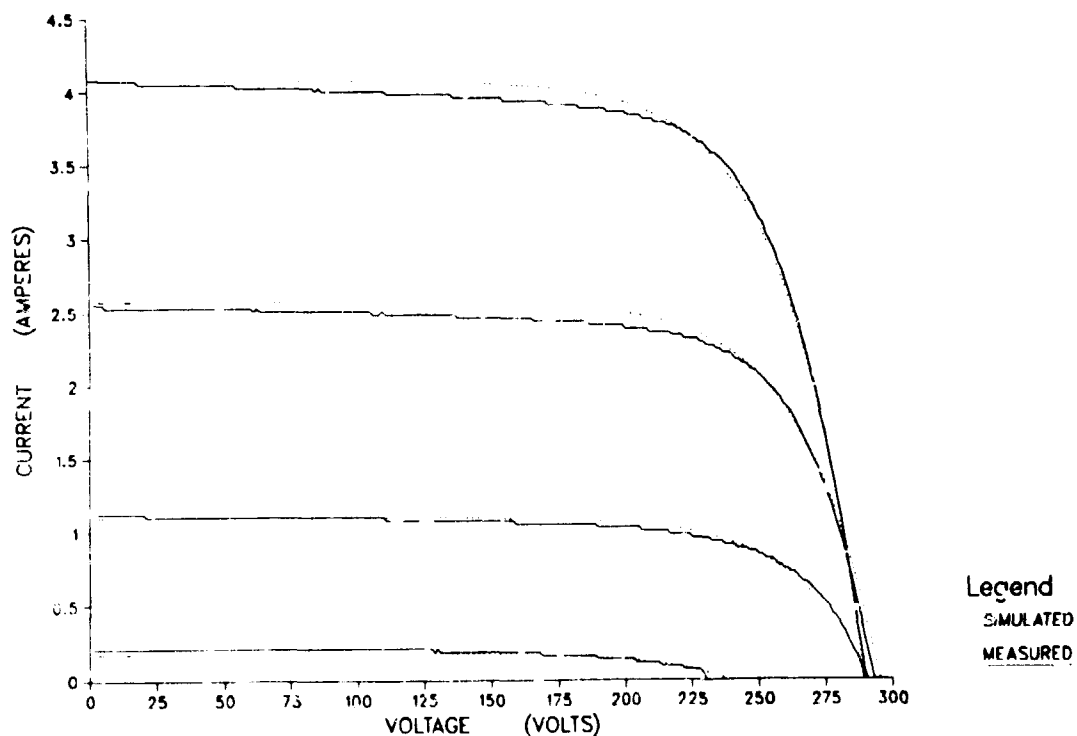
- IV CURVE TRANSLATION
- VOLTAGE CONTROL STRATEGIES
 - MAX POWER TRACKING
 - FIXED VOLTAGE
 - PILOT CELL

ENGINEERING SCIENCES AREA
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

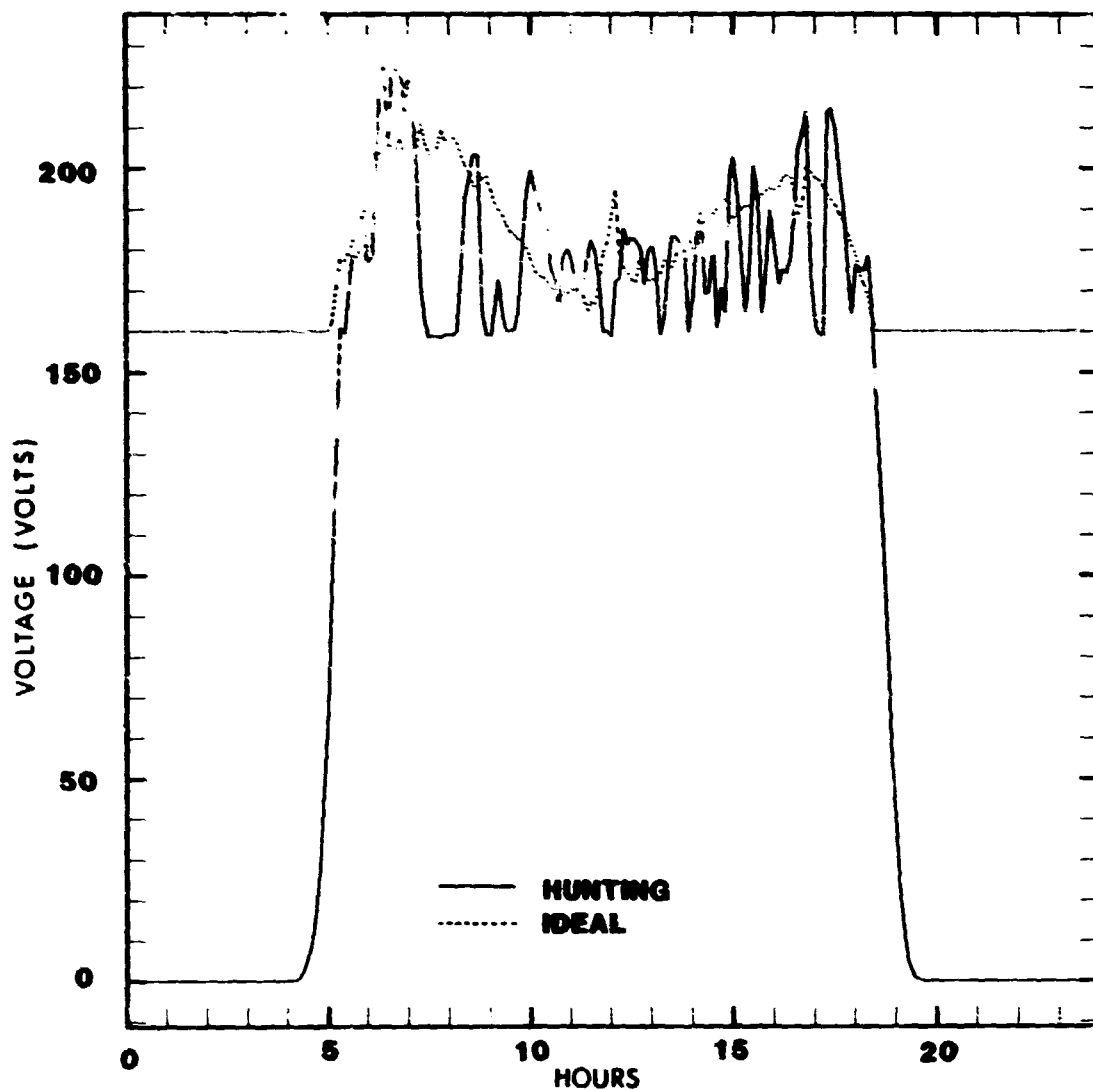
Effect of Insolation and Cell Temperature on I-V Curves



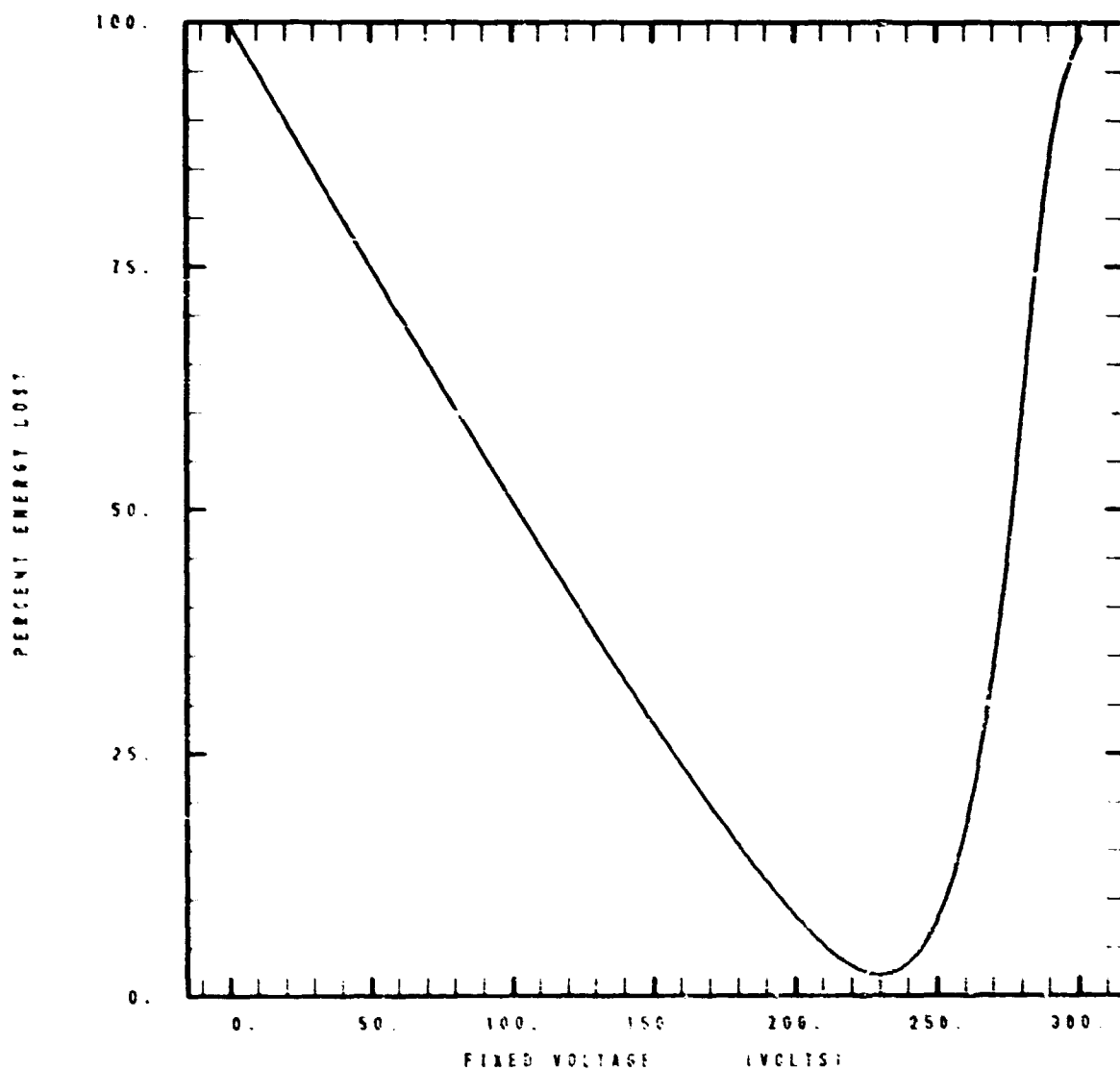
Measured and Simulated I-V Curves



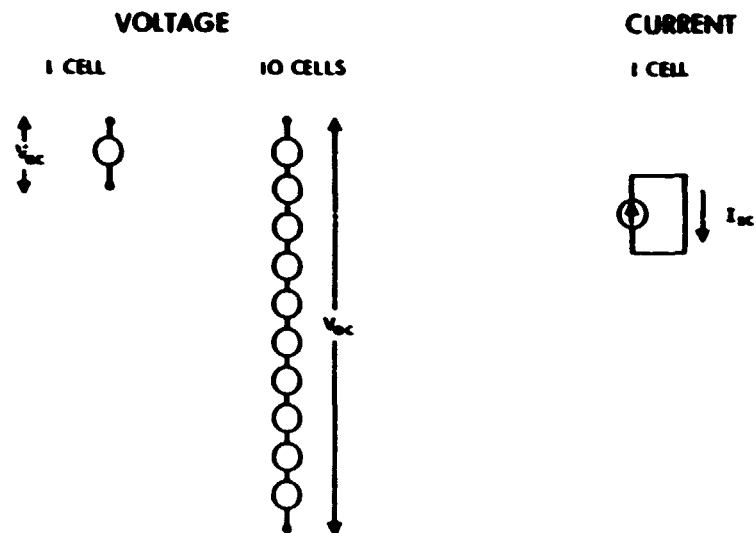
Measured and Calculated Voltages for Abacus
Inverter With "Searching" Maximum Power Tracker



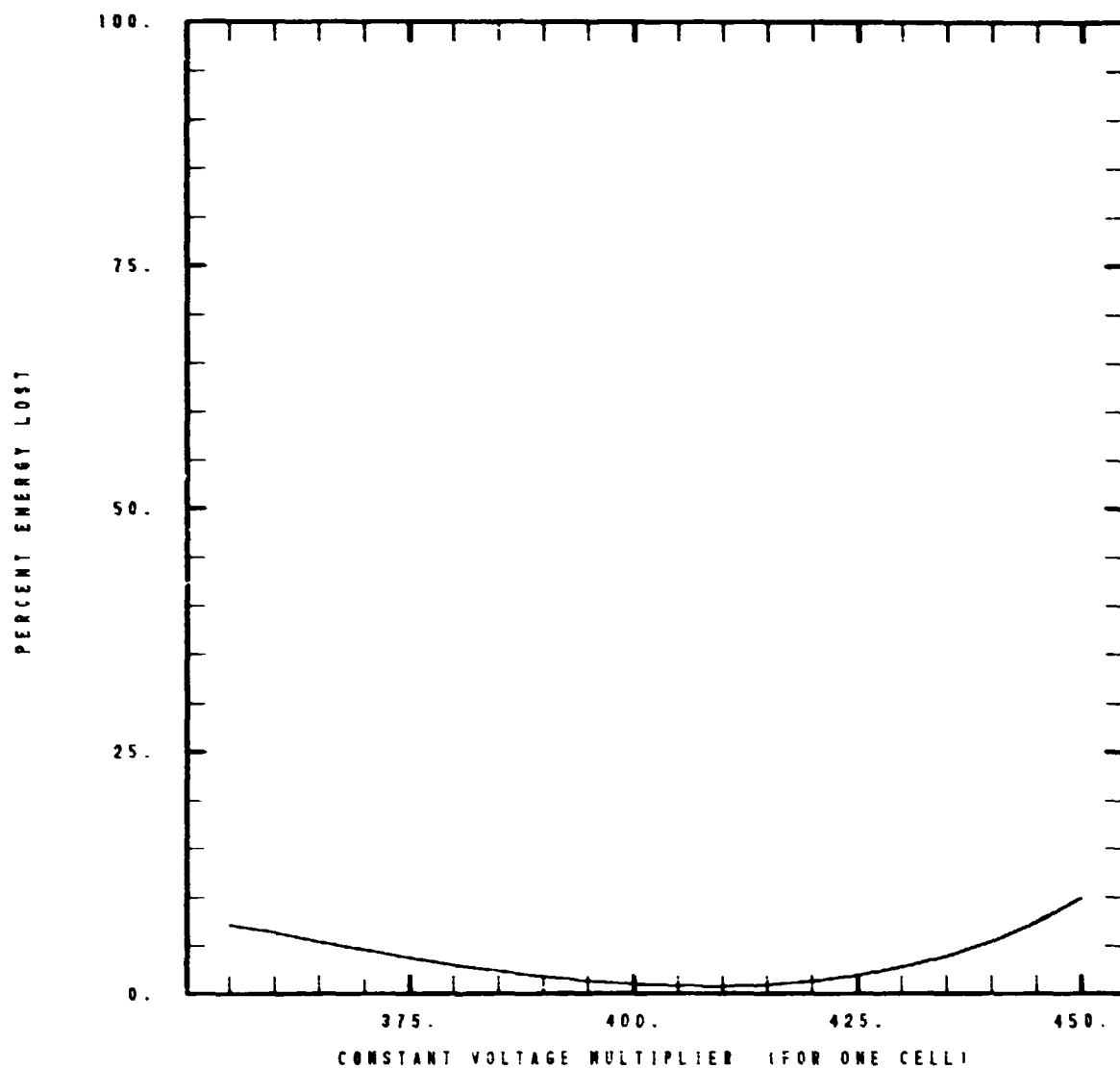
Energy Lost With Fixed-Voltage Operation



Pilot Cells

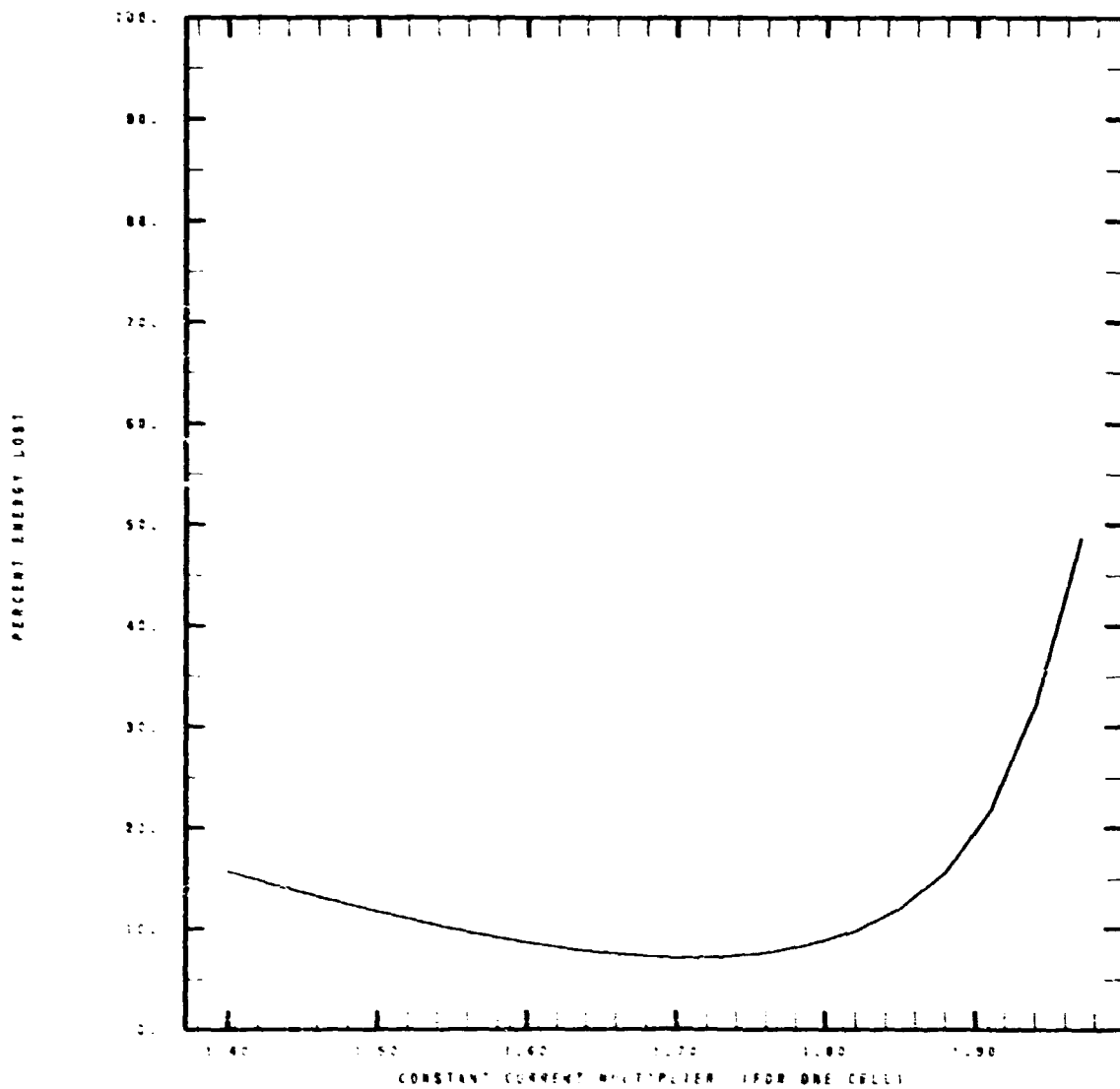


Energy Lost With Voltage-Multiplying Pilot Cell



04/01 16:35 CMULT

1



DAY 5 THROUGH DAY 28

Pilot Cell Experiments

BASED ON IV CURVES MEASURED EVERY 3 MINUTES
FOR 3 WEEKS IN JANUARY

TOTAL ENERGY AVAILABLE TO IDEAL MAX POWER TRACKER	67.3	
FIXED VOLTAGE	65.8	2.20% LOSS
VOLTAGE MULTIPLYING (1 CELL)	66.8	0.79% LOSS
VOLTAGE MULTIPLYING (10 CELLS)	66.5	1.17% LOSS
CURRENT MULTIPLYING (1 CELL)	62.5	7.13% LOSS

IRRADIANCE DATA FOR JPL TEST SITE

JET PROPULSION LABORATORY

R.W. Weaver

- JPL TEST SITE HAS BEEN RESTRUCTURED TO OBTAIN DATA FOR THE EARLY DETECTION OF PERFORMANCE PROBLEMS
- PERFORMANCE DATA MUST BE ADJUSTED TO REFERENCE CONDITIONS
- IRRADIANCE VALUES ARE KEY TO ADJUSTMENT PROCESS
- A COMPREHENSIVE SET OF IRRADIANCE MEASURING INSTRUMENTS HAVE BEEN INSTALLED

Irradiance Instruments

TRACKER MOUNTED: (± 0.25 DEG ACCURACY)

- EPPLEY PRECISION SPECTRAL PYRANOMETER (PSP)
- EPPLEY NORMAL INCIDENCE PYRHELIOMETER (NIP)
- JPL FILTERED RADIOMETER 500, 858 AND 940 NANOMETERS

FIXED:

HORIZONTAL:

- EPPLEY PSP
- LI-COR PYRANOMETER

TILTED AT 34 DEG.:

- EPPLEY PSP
- LI-COR PYRANOMETER
- 11 REFERENCE CELLS

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Instrument Calibration

PYRANOMETERS:

- ONE EPPLEY PSP WAS CALIBRATED BY NOAA
- ALL WERE MOUNTED HORIZONTALLY
- DATA WERE TAKEN FOR ALL
- THE CALIBRATED PSP WAS USED AS A STANDARD FOR ALL OTHERS

NIP:

- USED EPPLEY CALIBRATION VALUES

FILTERED RADIOMETER:

- USED SUPPLIED CALIBRATION VALUES
(JPL SOLAR ENERGY CONVERSION SYSTEMS SECTION, 341)

Irradiance Data

MEASURED: (EVERY 5 MINUTES FROM SUN UP TO SUN DOWN)

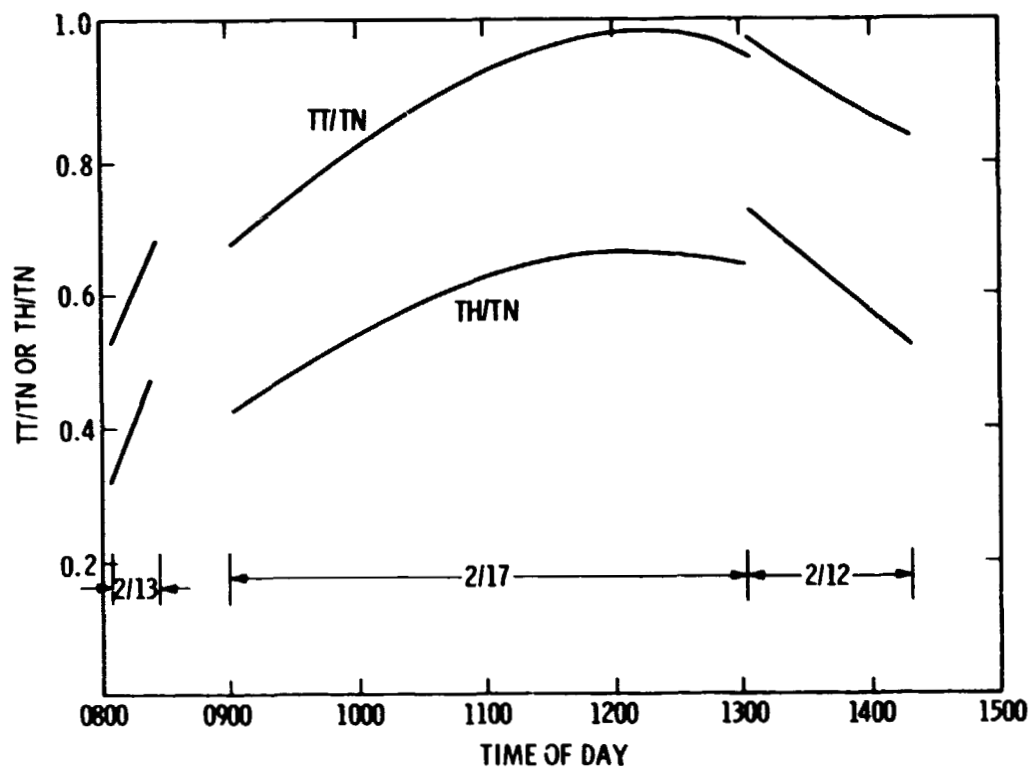
- DIRECT NORMAL (DN)
- TOTAL NORMAL (TN)
- TOTAL HORIZONTAL (TH)
- TOTAL TILTED (TT)
- TILTED TOTALS FOR EACH REF. CELL
- RADIOMETER

COMPUTED:

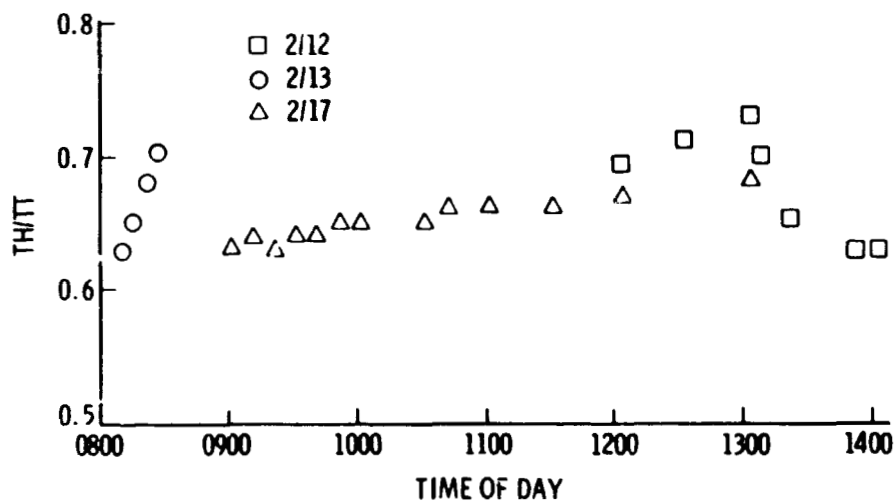
- TURBIDITY COEFFICIENT
- WATER VAPOR
- AIR MASS (FROM BAROMETRIC PRESSURE)

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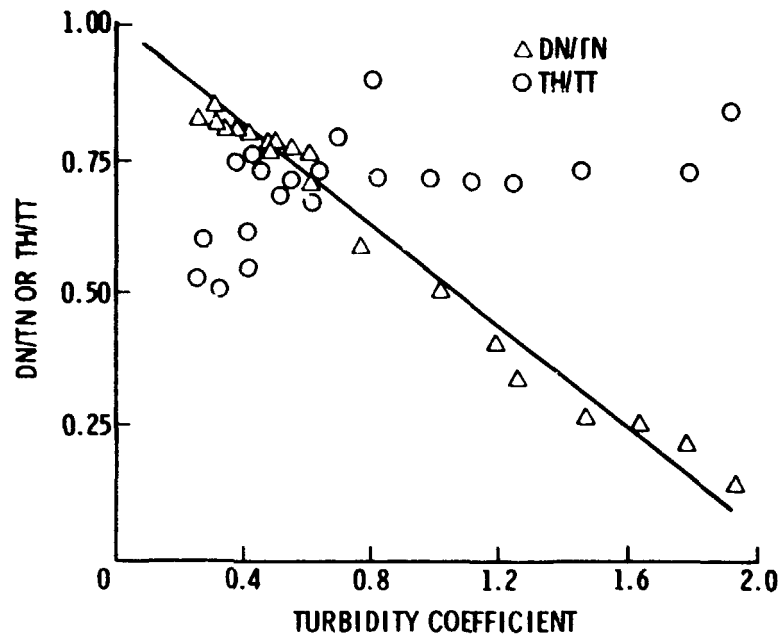
Results: Total Tilt (TT) and Total
Horizontal (TH) Fractions



Results: Total Horizontal to Total
Tilted Ratio vs Time of Day



Results: Direct Normal to Total Normal vs Turbidity
Coefficient; Total Horizontal to Total Tilted
vs Turbidity Coefficient



Summary

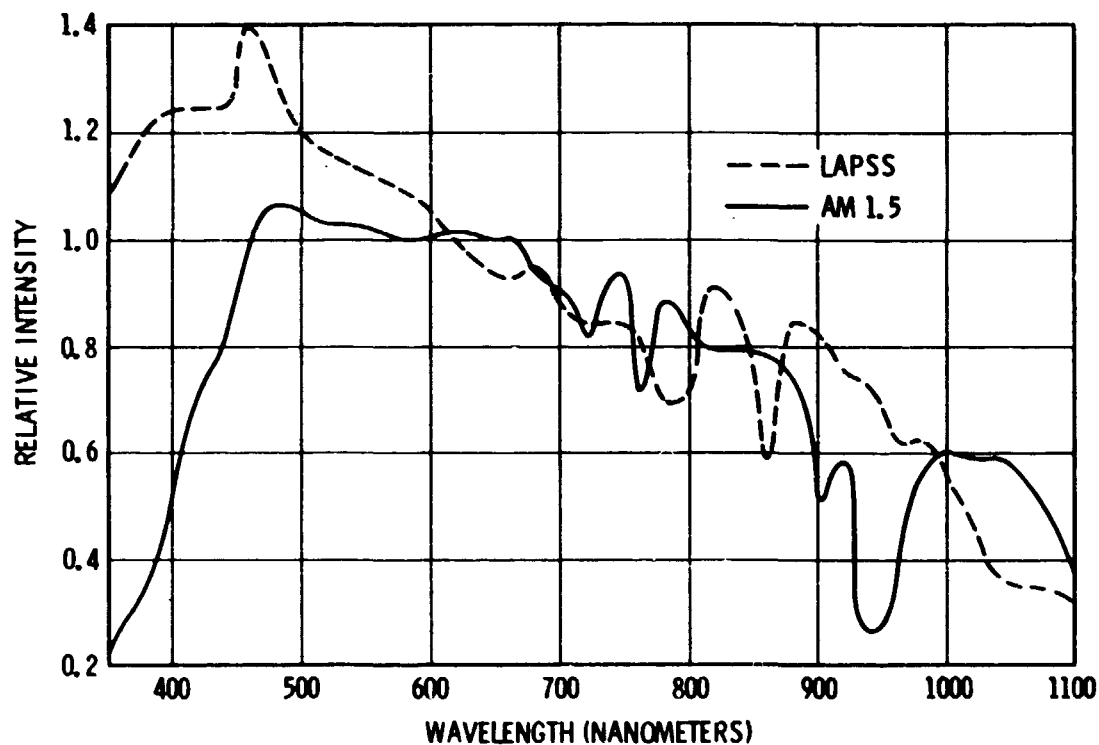
- TURBIDITY COEFFICIENT IS A GOOD INDICATOR OF THE DIFFUSE IRRADIANCE FRACTION IN THE NORMAL PLANE
- POOR CORRELATION BETWEEN TURBIDITY AND THE RATIO OF TOTAL HORIZONTAL TO TOTAL TILTED
- TRANSFORMATIONS BETWEEN THE NORMAL, HORIZONTAL AND TILTED PLANES MAY REQUIRE DIFFUSE SOURCE DATA
- THE REFERENCE IRRADIANCE SHOULD BE MEASURED IN THE TILT PLANE

AM1.5 FILTERING SYSTEM FOR LAPSS

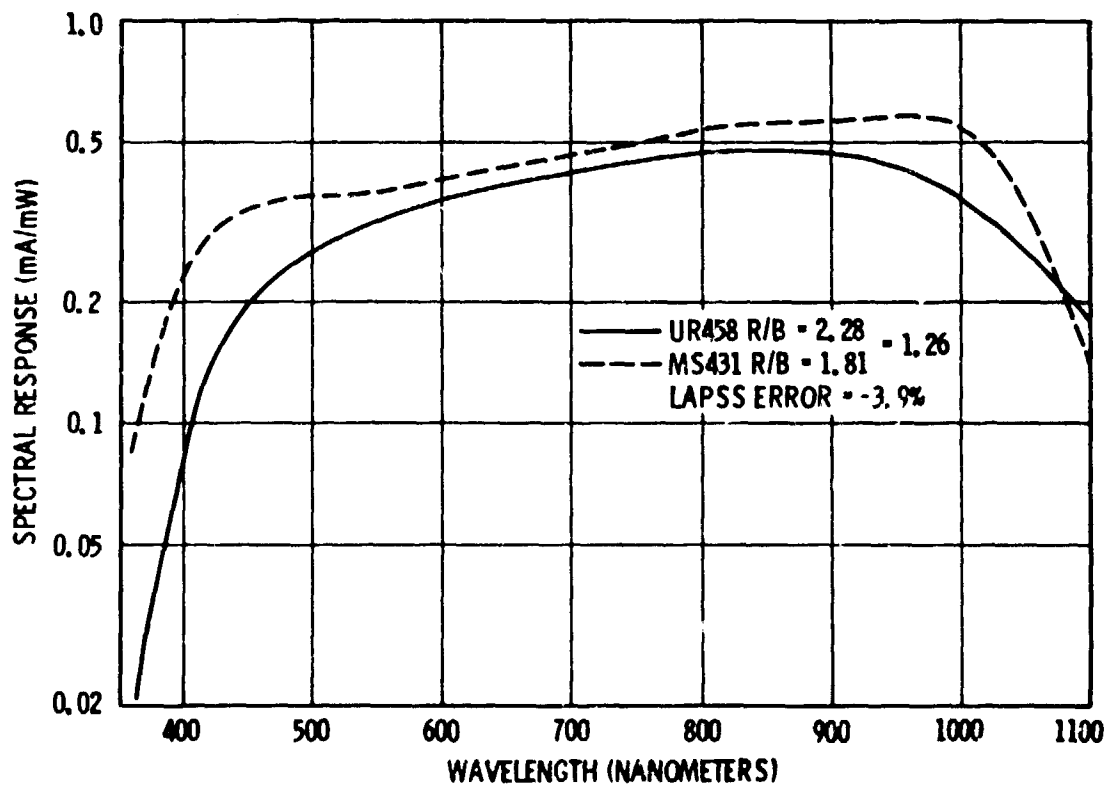
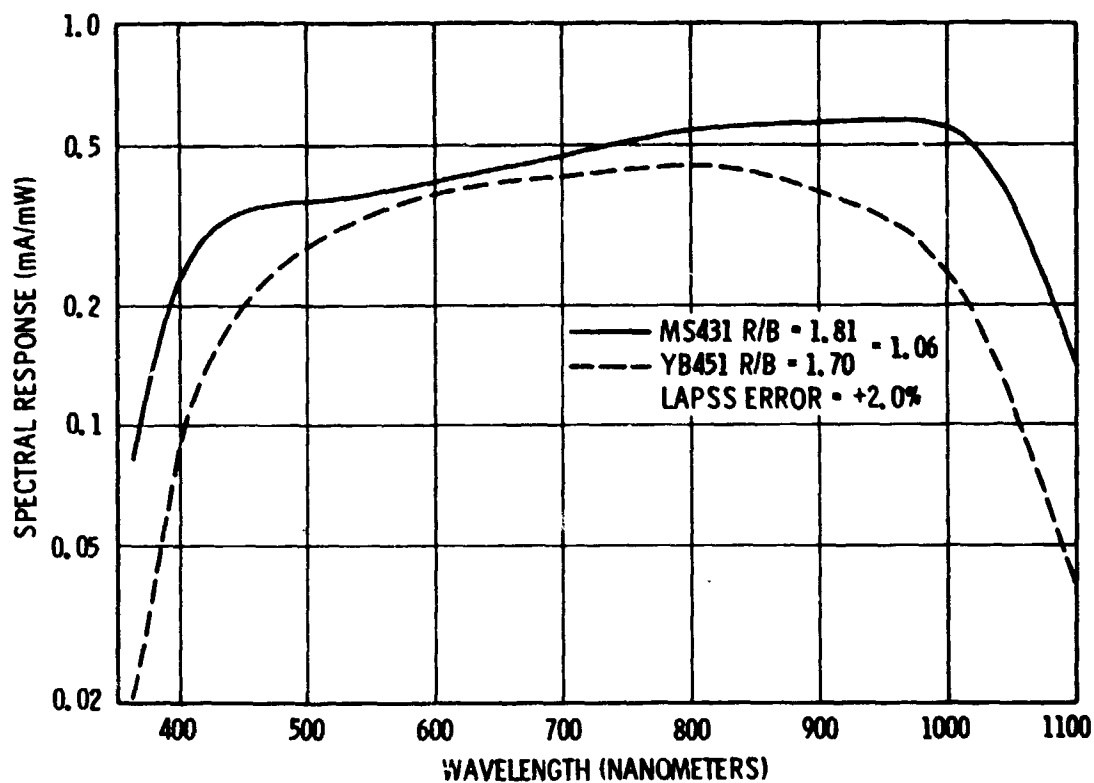
JET PROPULSION LABORATORY

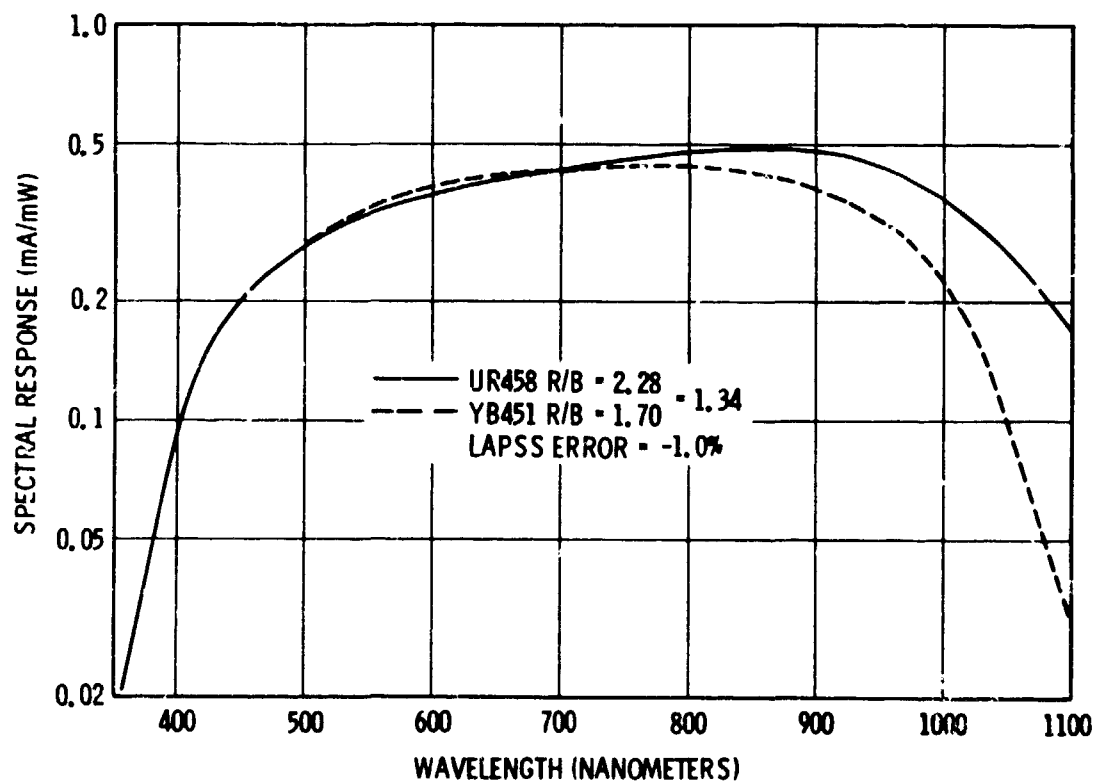
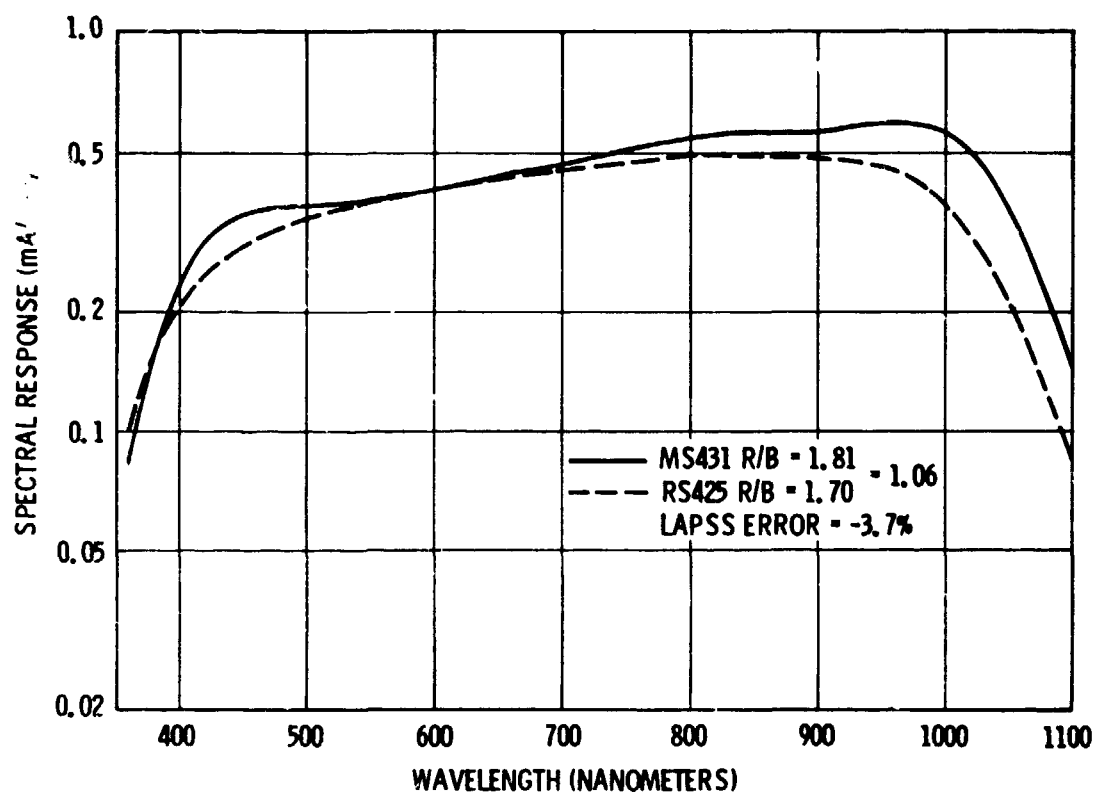
C.H. Seaman

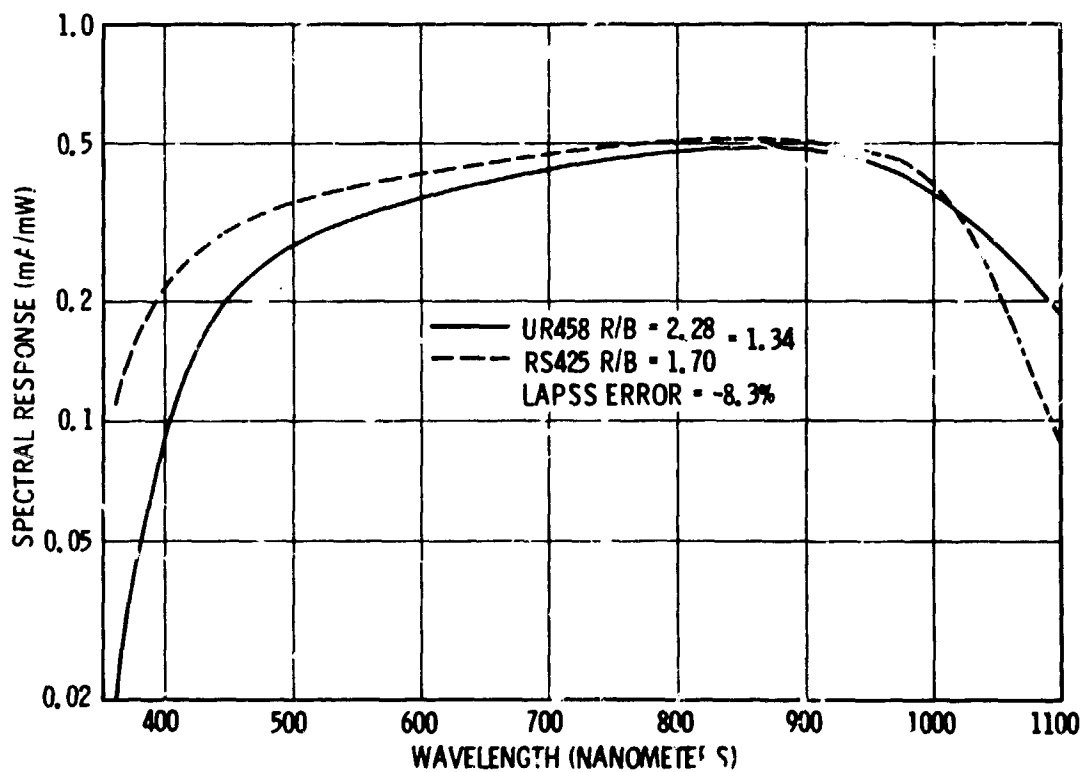
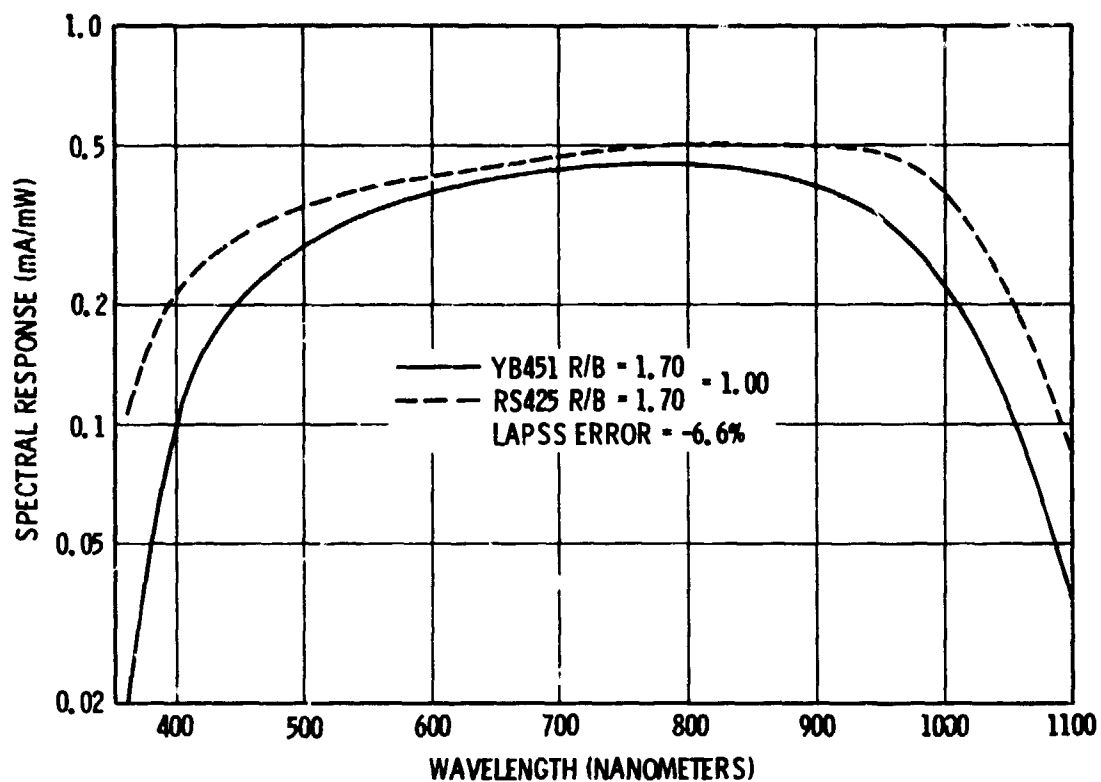
Spectral Irradiance, Unfiltered LAPSS and AM1.5



Spectral Response Comparisons of Reference and Test Cells







The Mismatch Factor M

$$M = \frac{(\sum E_{Si} R_{Ci} \Delta_i) (\sum E_{Ai} R_{Ri} \Delta_i)}{(\sum E_{Si} R_{Ri} \Delta_i) (\sum E_{Ai} R_{Ci} \Delta_i)}$$

E_{Si} - LAPSS SPECTRAL IRRADIANCE

E_{Ai} - AM 1.5 SPECTRAL IRRADIANCE

R_{Ci} - TEST CELL SPECTRAL RESPONSE

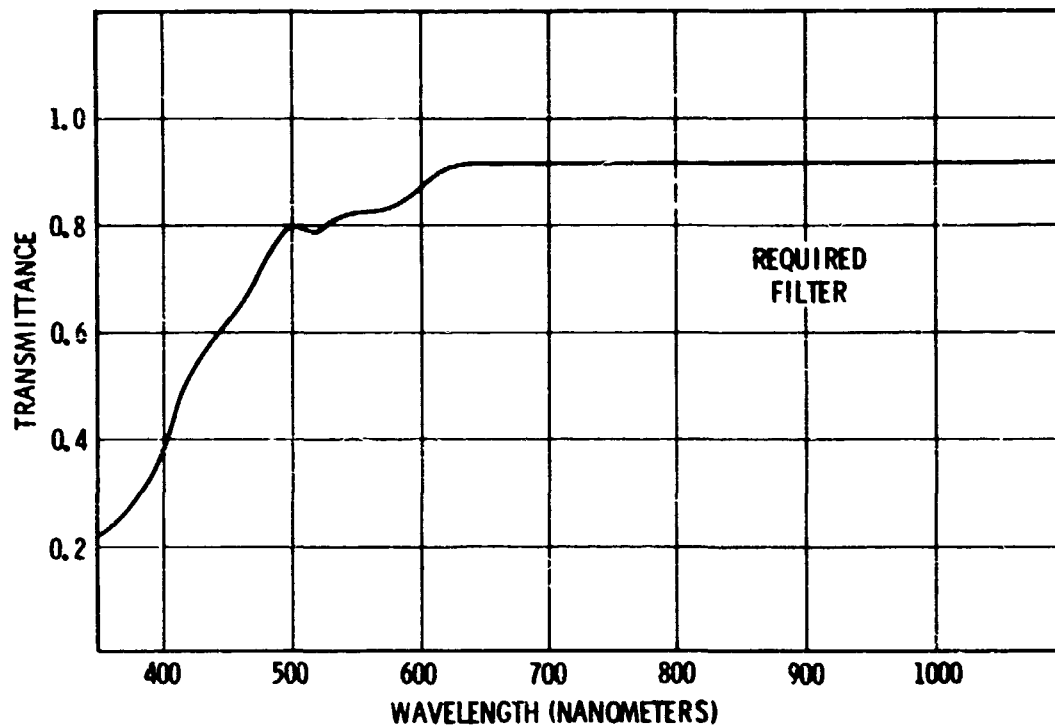
R_{Ri} - REFERENCE CELL SPECTRAL RESPONSE

ERROR - M-1

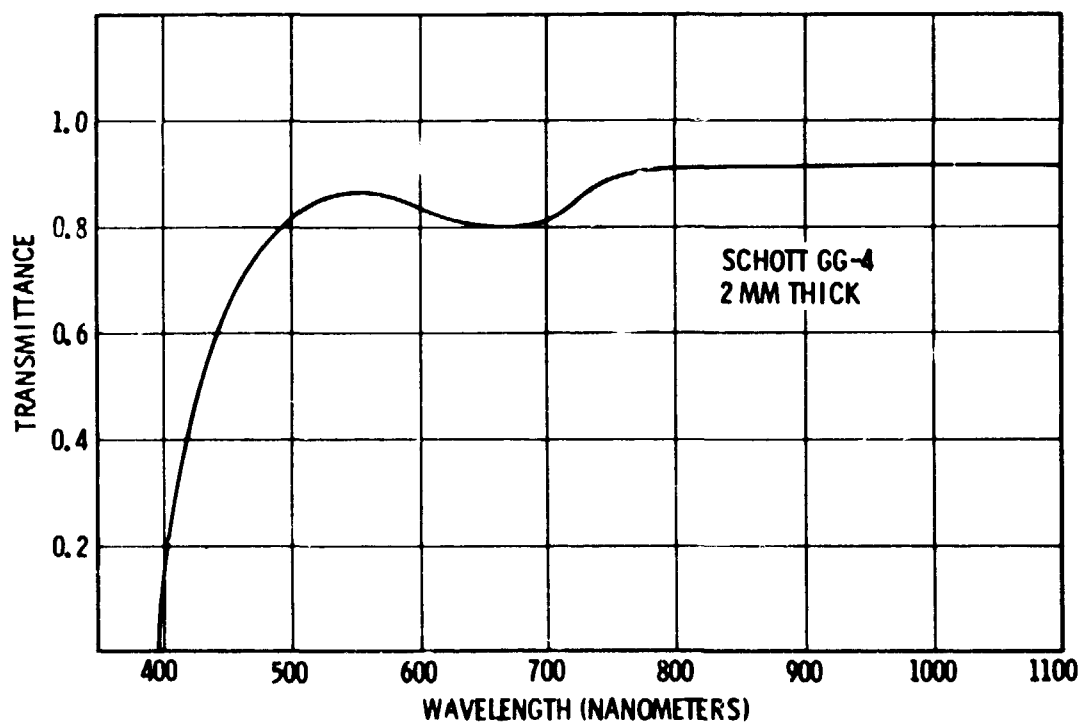
Measured Error Using Unfiltered LAPSS

	PAIR	R/B	$\frac{(R/B)_C}{(R/B)_R}$	% ERROR NO FILTER
C	MS 431	1.81	1.06	+2.0
R	YB 451	1.70		
C	UR 458	2.28	1.26	-3.9
R	MS 431	1.81		
C	MS 431	1.81	1.06	-3.7
R	RS 425	1.70		
C	UR 458	2.28	1.34	-1.0
R	YB 451	1.70		
C	YB 451	1.70	1.00	-6.6
R	RS 425	1.70		
C	UR 458	2.28	1.34	-8.3
R	RS 425	1.70		
ERROR EXPECTATION VALUE				4.3

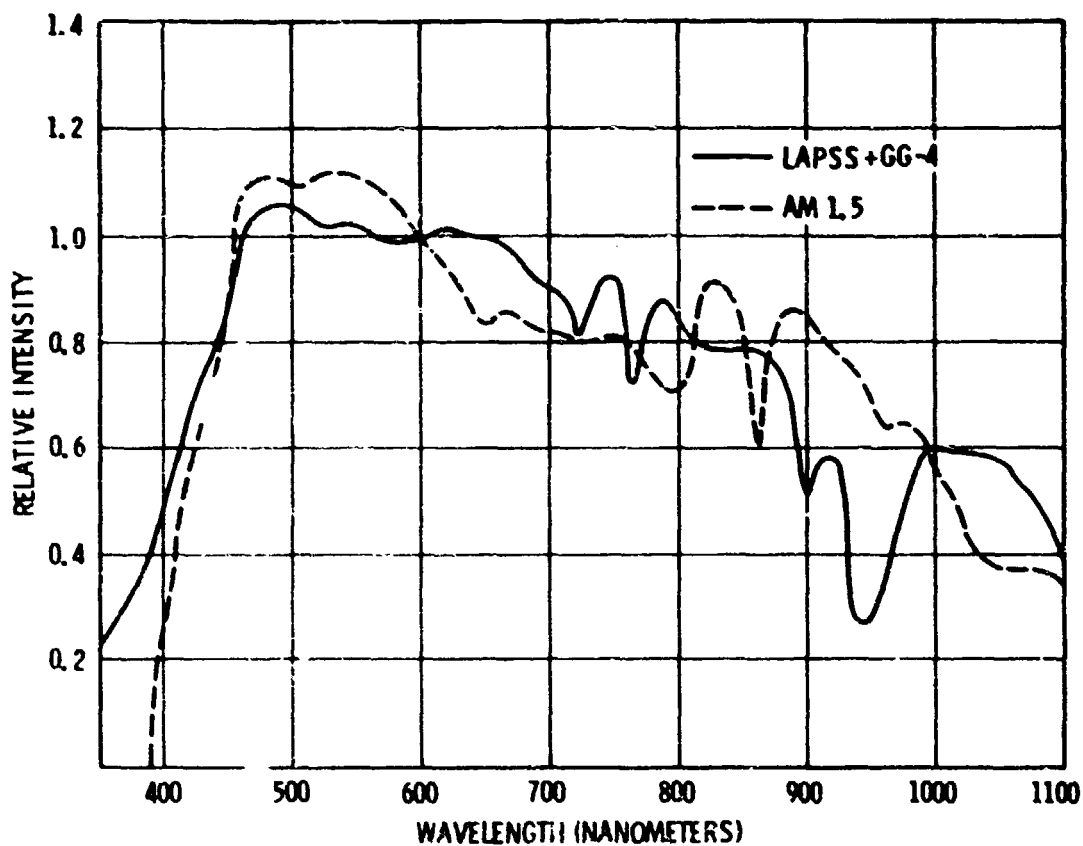
Required Correction Filter



Schott GG-4 Filter



Spectral Irradiance, Filtered LAPSS and AM1.5



Calculated Errors Using Filtered LAPSS

	PAIR	CALCULATED % ERROR
C R	MS 431 YB 451	0.0
C R	UR 458 RS 425	-0.2
C R	MS 431 RS 425	+0.1
C R	UR 458 YB 451	+0.2
C R	YB 451 RS 425	+0.1
C R	UR 458 RS 425	-0.2

Measured Errors Before and After Filtering

	PAIR	R/B	$\frac{(R/B)_C}{(R/B)_R}$	% ERROR NO FILTER	% ERROR FILTER
C R	MS 431 YB 451	1.81 1.70	1.06	+2.0	-0.1
C R	UR 458 MS 431	2.28 1.81	1.26	-3.9	-0.1
C R	MS 431 RS 425	1.81 1.70	1.06	-3.7	+0.2
C R	UR 458 YB 451	2.28 1.70	1.34	-1.0	+1.0
C R	YB 451 RS 425	1.70 1.70	1.00	-6.6	0.0
C R	UR 458 RS 425	2.28 1.70	1.34	-8.3	+0.9
ERROR EXPECTATION VALUE				4.3	0.4

RESIDENTIAL ARRAY RESEARCH

JET PROPULSION LABORATORY

A. H. Wilson

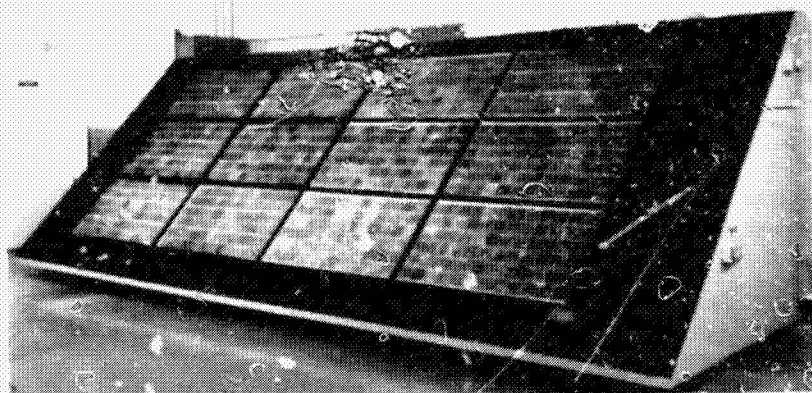
Residential Array Technology Gaps

- **Water Sealing**
 - Techniques for Horizontal Joints
 - Concern Over Seal Durability
- **Module Support Structure**
 - 2 vs 4 Sides Module Support
 - Edge Protection of Glass
 - Methods to Minimize Field Labor
 - Installation of Frame Structure on Roof
 - Installation and Replacement of Modules
- **Electrical Safety**
 - Allowable Wiring and Connectors
 - Concern With Conductive Structures

JPL In-House Residential Array Research Activity: Objective and Approach

- Synthesize Residential Array Solution to Identified Gaps:
 - Light Weight, Non-Conductive Structural Frames
 - Non-Conductive to Eliminate Need for Grounding
 - Factory Pre-Assembly } to Minimize Field Labor and
 - Integral Scaffolding } Provide 4-Side Module Support
 - Integral Drain Gutters to Achieve Long-Life Water Sealing
 - Snap-Ring-Type Module Retainer
 - Underground Feeder Cable to Meet Proposed 1984 NEC Code Constraints
 - Module Support Brackets to Facilitate Module Installation
- Fabricate Array Research Model to Evaluate:
 - Structural Loading Capabilities
 - Thermal Expansion Effects
 - Both Parallel and Series Circuit Requirements
 - Module Installation and Replacement Ideas
 - Weathering and Water Sealing Capabilities
 - Aesthetic Appearance

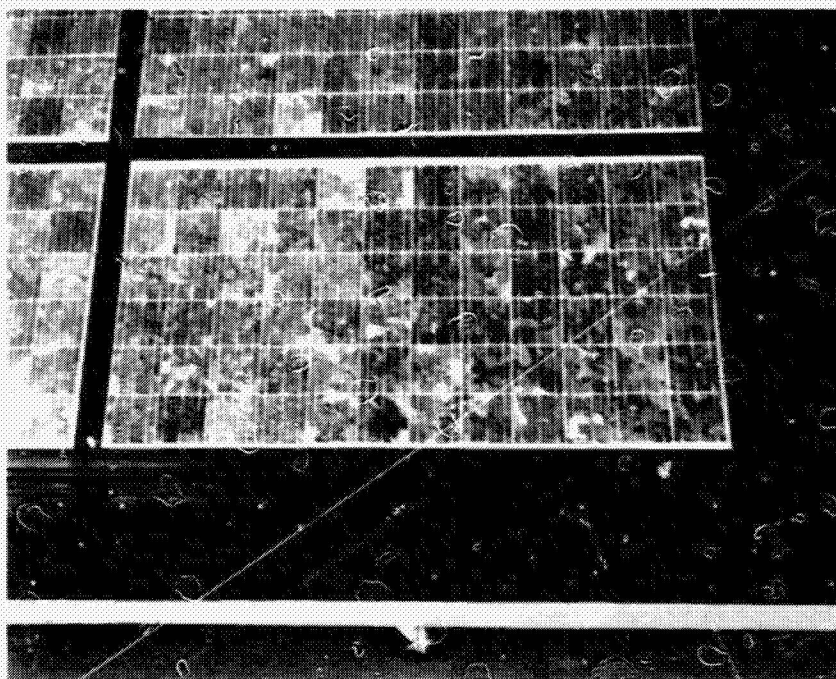
Residential Array Research Model



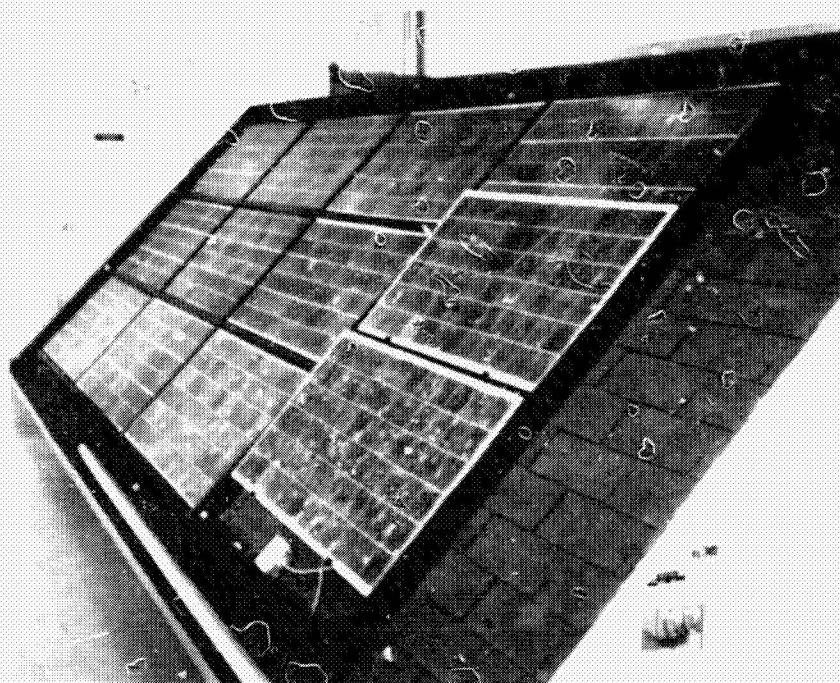
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Detail: Corner of Model

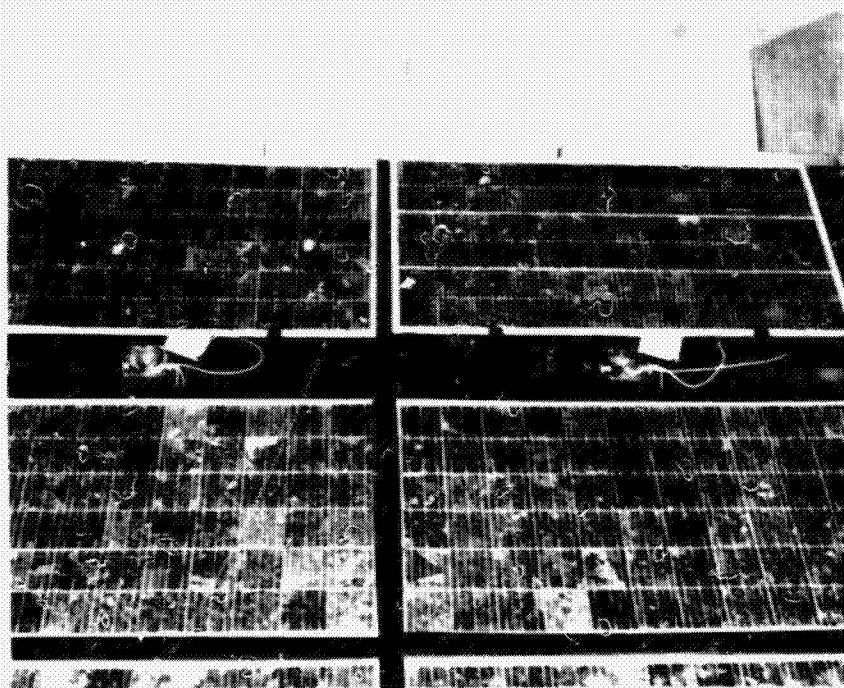
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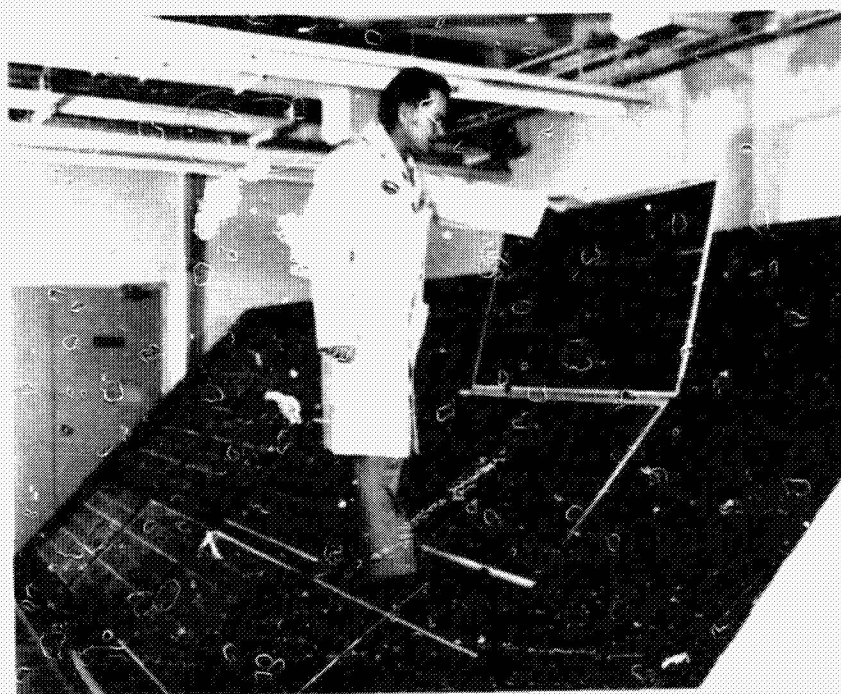
Model With J-Box Exposed



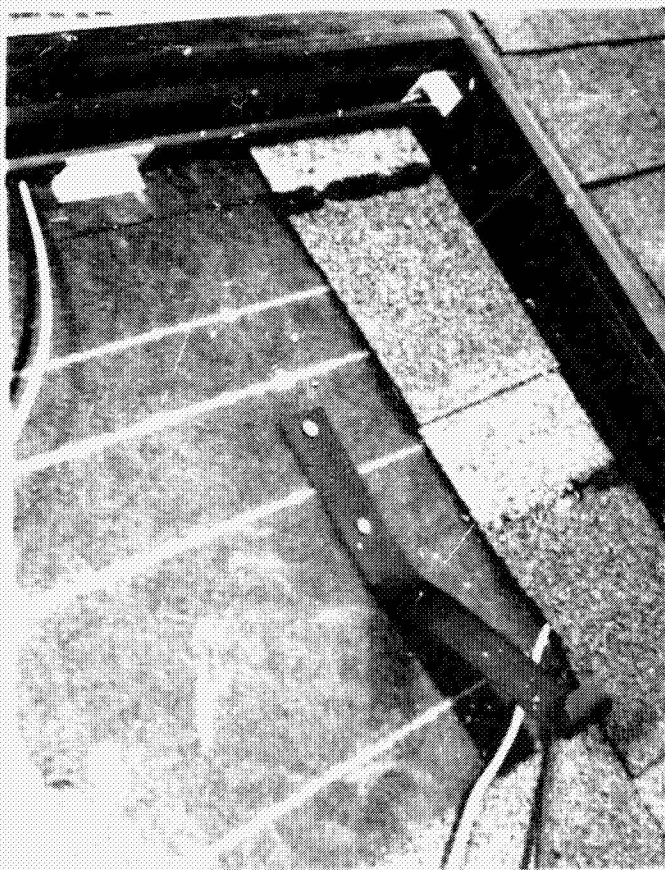
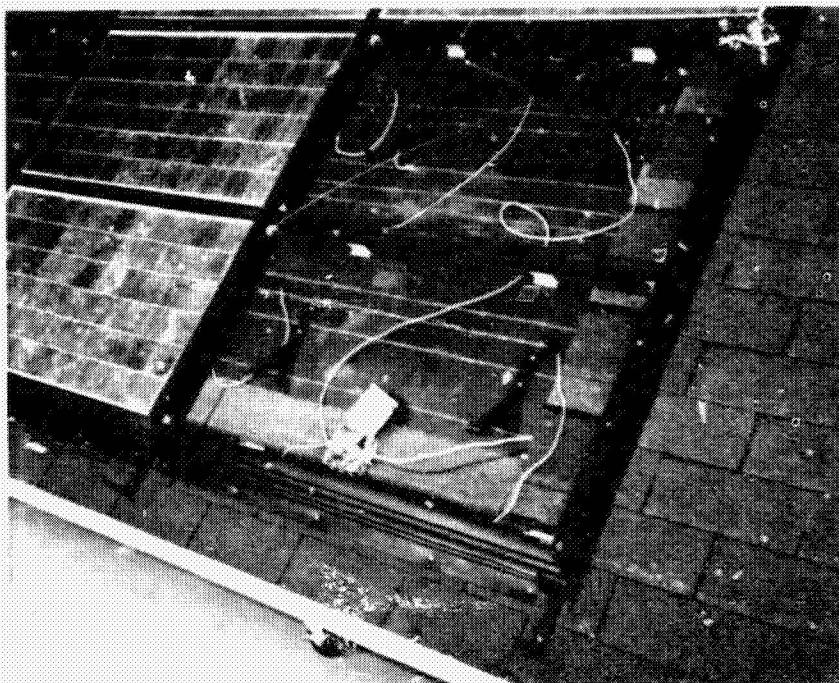
Upper Modules Supported by Brackets



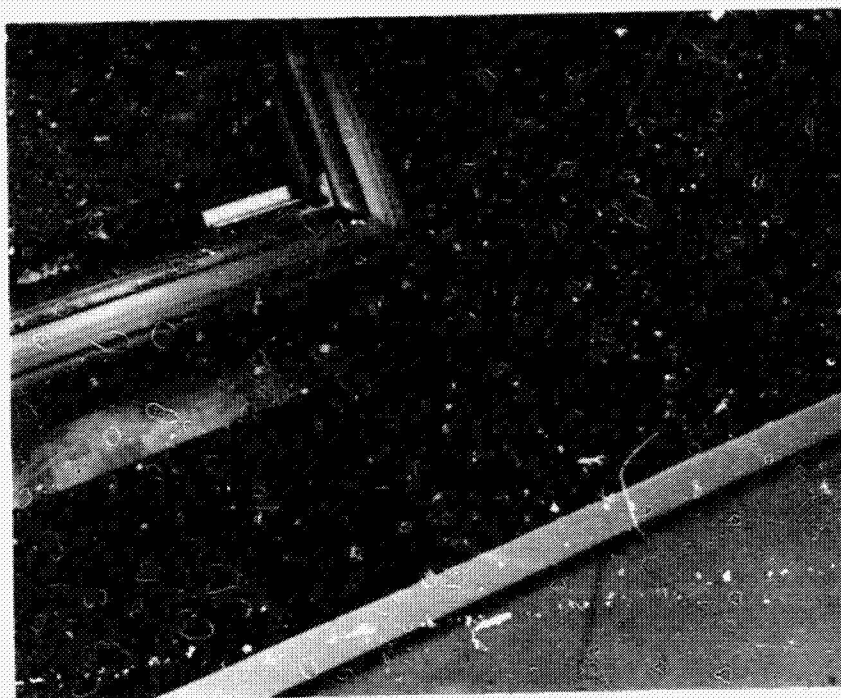
Technician Replacing Module



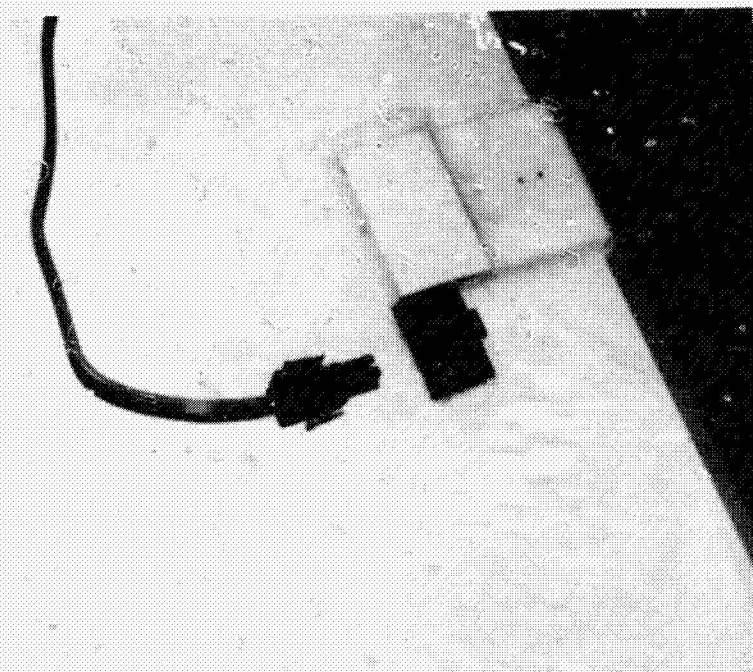
Details of Model Construction



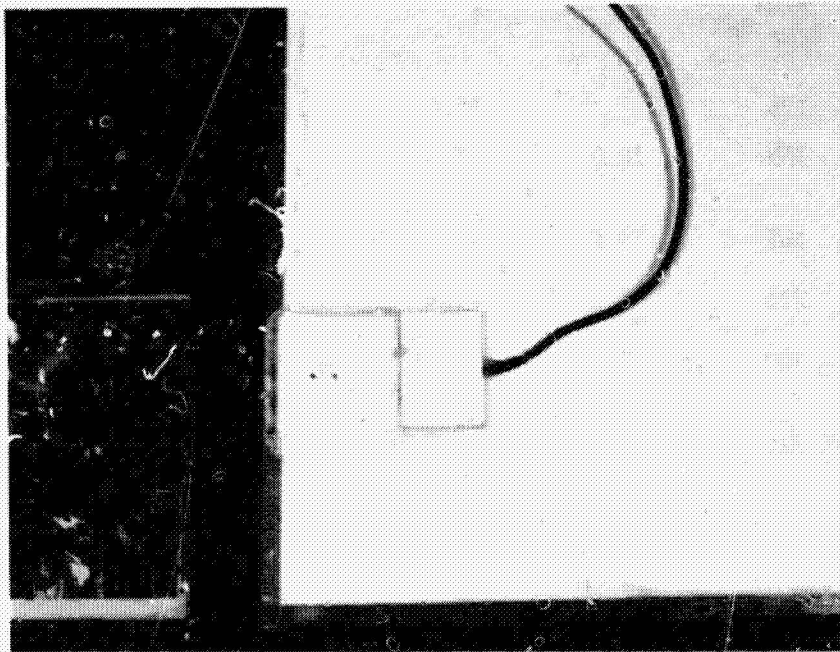
Details of Model Construction



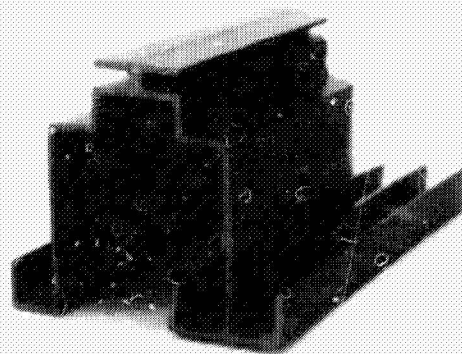
Modification to Meet UL Requirements (Connector)



Modification to Meet UL Requirements
(Lead, Underground Feeder Wire)



Cross Section of Plastic Frame Extrusion



UV-Stabilized Extrudable Thermoplastics Properties

MATERIAL	DEFLEC- TION TEMP °F	TENSILE 10 ³ PSI	COMPRESSIVE 10 ³ PSI	FLEXURAL 10 ³ PSI	FLEXURAL MODULUS 10 ³ PSI	SUPPLIER
ACETAL	225		16.0	13.0	375	DUPONT
NYLON	365	10.0	13.0	14.0	390	DUPONT, LNP
PHENYLENE OXIDE	265	9.6	16.4	13.5	360	GEN. ELEC.
POLYCARBONATE	220	7.0	11.0	13.0	300	MOBAY
POLYSULFONE	400			12.4	330	ICI AMERICA LNP
CHLORINATED PVC 215		7.5	9.0	14.5	380	GOODRICH
PVC (REF. POINT)	155-180	6.0	8.0	10.0	300	GOODRICH, KOHINOR

APRIL, 1932

Summary

- Array Concepts Have Been Developed and Discussed

Future Work

- Continue Experiments Using Research Model
- Report on Residential Array Research Model Work

VOLTAGE BREAKDOWN OF PV INSULATING MATERIALS

JET PROPULSION LABORATORY

G.R. Mon

Program Objectives

- Characterize Statistical Voltage Breakdown Behavior of Electrical Insulation Materials and Composites Used in Photovoltaic Modules
- Develop Algorithms to Predict Module Field-Failure Probabilities at System Operating Voltages
- Develop Algorithms for Selecting Insulation Systems With Least Life-Cycle Energy Cost

Approach

- Break Down Many Test Areas ($A_T = 0.785\text{-in}^2$) of Candidate Insulation Systems
- Develop Statistical Breakdown Curves for Each System Tested
- Selectively Age Candidate Systems in an Environmental Aging Chamber
- Conduct Additional Breakdown Tests at Reasonable Intervals During the Aging Process to Ascertain the Effects of Aging on the Voltage Breakdown Characteristics of the Candidate Insulation Systems

Materials Tested to Date

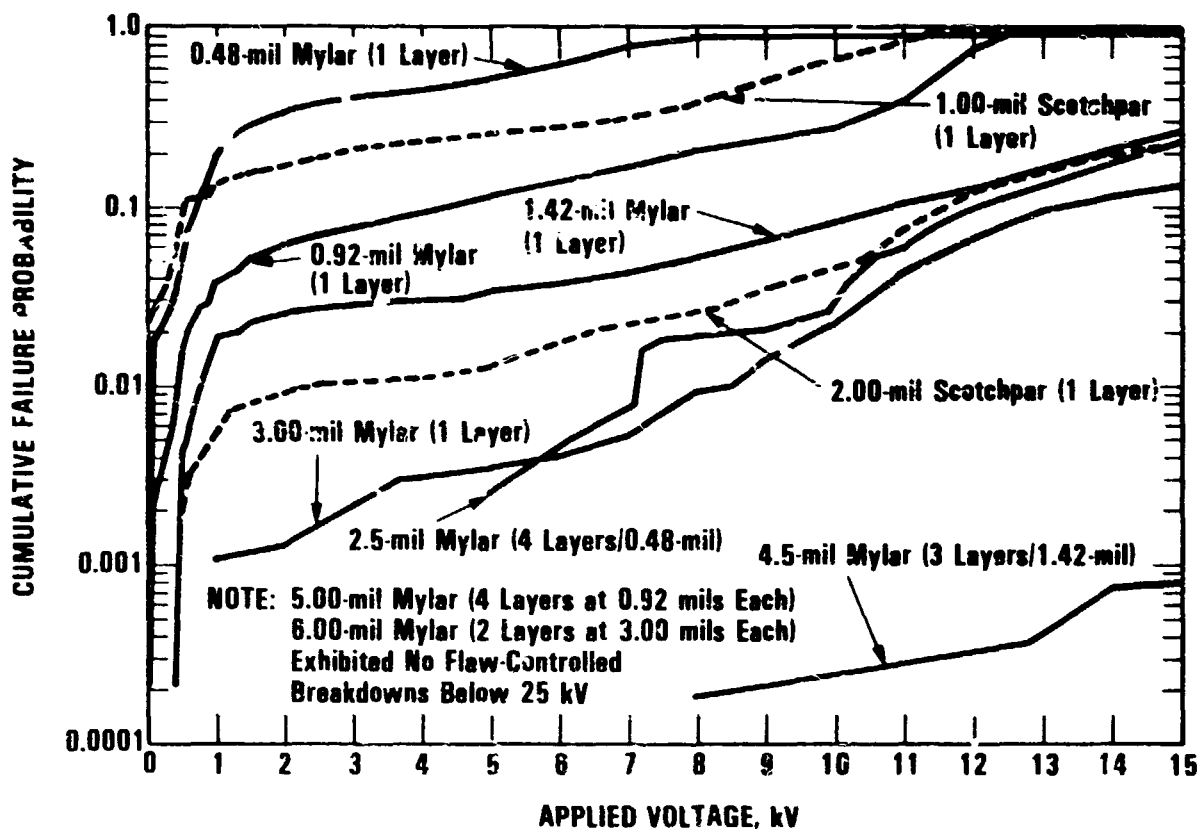
TEST NO.	MATERIAL	THICKNESS (mils)	NO. OF LAYERS	THICKNESS PER LAYER (mils)	NO. OF TEST POINTS
1	Mylar	0.48	1	0.48	4272
2	Mylar	0.92	1	0.92	4608
3	Mylar	1.42	1	1.42	4608
4	Mylar	3.00	1	3.00	4608
5	Scotchpar: 10 CP 3110	1.00	1	1.00	1034
6	Scotchpar: 20 CP 3110	2.00	1	2.00	968
7	Mylar - Unaged Aged*	2.50	4	0.48	385 507
8	Mylar	4.50	3	1.42	5363
9	Mylar	5.00	4	0.92	5280
10	Mylar	8.00	2	3.00	3550
11	EVA	20.00	1	20.00	1037
12	EMA	24.00	1	24.00	429

13	Tedlar: 100BG30TR	1.0	1	1.0	176
14	Tedlar: 100BG30UT 88040 Primer	1.0	1	1.0	1056
15	Tedlar: 100SG30TR	1.0	1	1.0	176
16	Tedlar: 150BL30WH	1.5	1	1.5	1880
17	Tedlar: 200BS30WH 88040 Primer	2.0	1	2.0	2575
18	Tedlar: 200SG40TR	2.0	1	2.0	264
19	Tedlar: Milky	4.0	1	4.0	1959
20	Tedlar: Experimental WH Unaged Aged*	4.0	1	4.0	381 876
21	Polyester	4.0	1	4.0	441
22	Tedlar/Aluminum/Polyester/ Tedlar TAPT TPAT	8.0	4	1.5/0.7/4.0/1.5	1840 1421

*Aged 1600 h at 40°C/93% RH, Then Dehumidified

ORIGINAL RECORD
OF PERFORMANCE

Voltage Breakdown Characteristics of Single-Layer
and Multilayer Polyethylene Terephthalate
Insulation Films (per Unit Test Area: $A_T = 0.785 \text{ in}^2$)



Theoretical Film and Module Failure Probabilities

- The Breakdown Probability of a Single Test Area ($A_T = 0.785\text{-in}^2$), Determined by Measurement, Is p .

The Breakdown Probability of a Test Area of a Multilayer Film is $p_m = \prod_{i=1}^m p_i$

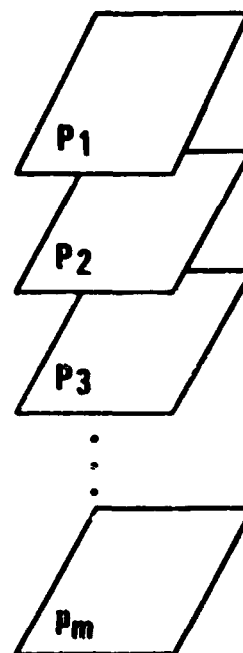
Where

p_i = Breakdown Probability of a Test Area of Layer i
 m = Number of Layers

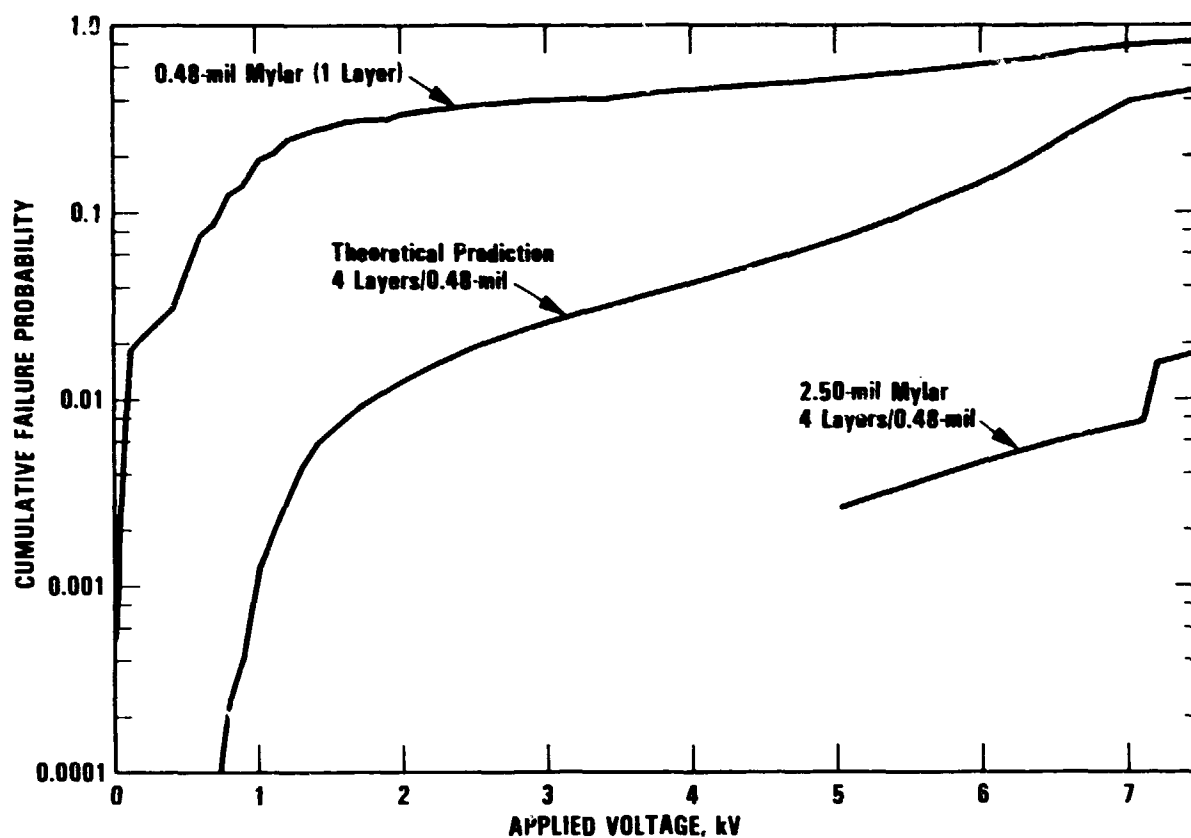
- If All of the Layers Are Identical, Then $p_m = p^m$

- The Breakdown Probability of a Module Using Multilayer Insulating Films is $p_{MOD} = 1 - (1 - p_m)^n$

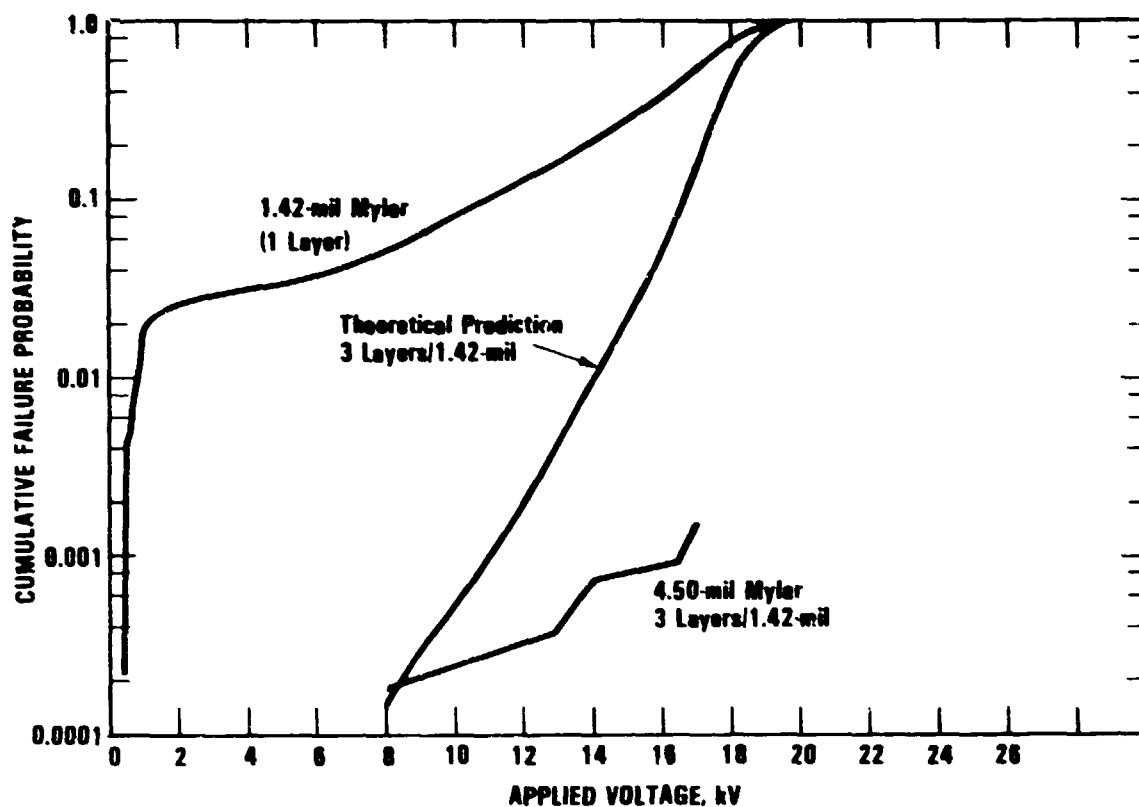
Where $n = \begin{Bmatrix} 1467 \\ 2936 \\ 5867 \end{Bmatrix}$ for $\begin{Bmatrix} 2X2\text{-ft} \\ 4X4\text{-ft} \\ 4X8\text{-ft} \end{Bmatrix}$ Modules



Theoretical vs Measured Voltage Breakdown Characteristics
of Multilayer Mylar Insulation Films: Single Layer, 0.48 mils

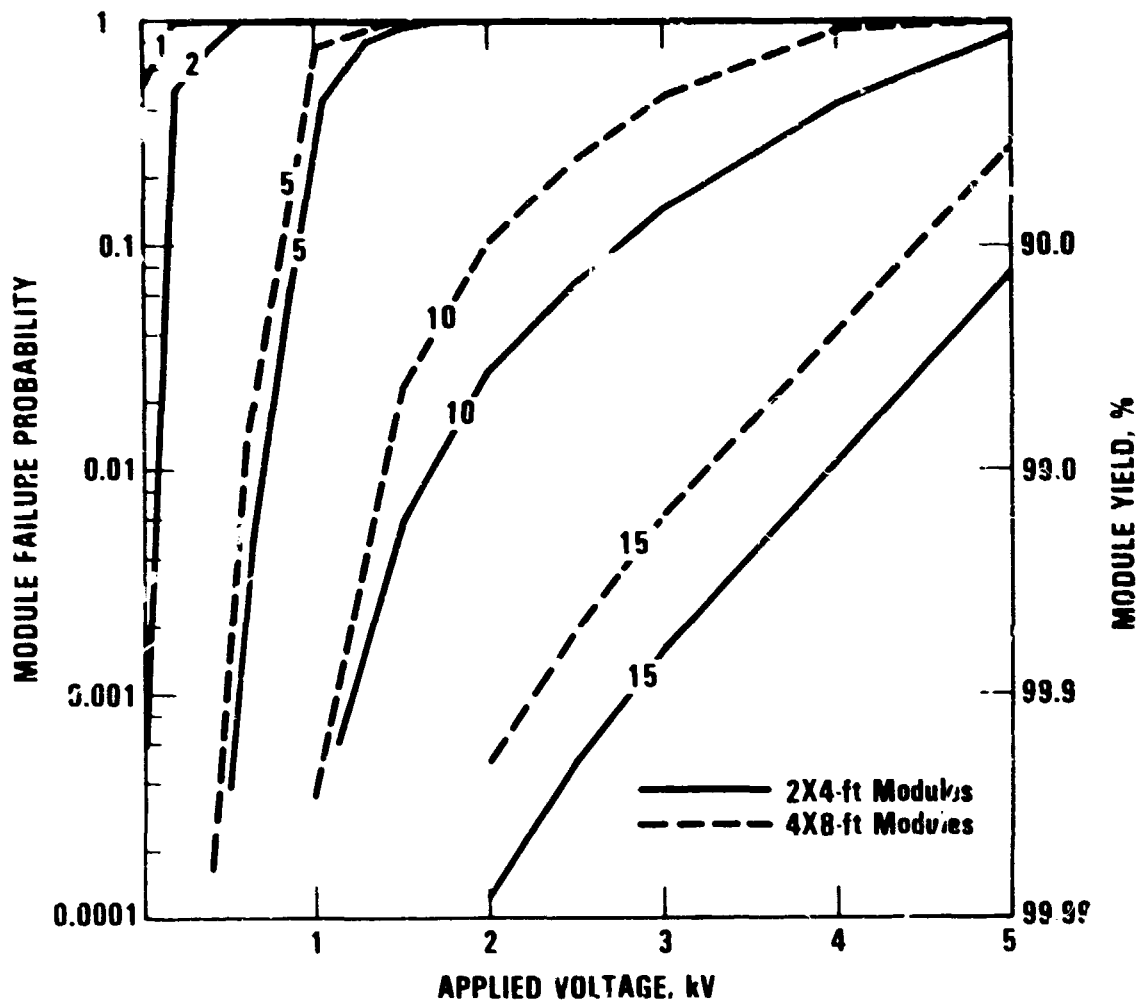


Theoretical vs Measured Voltage Breakdown Characteristics
of Multilayer Mylar Insulation Films: Single Layer, 1.42 mils

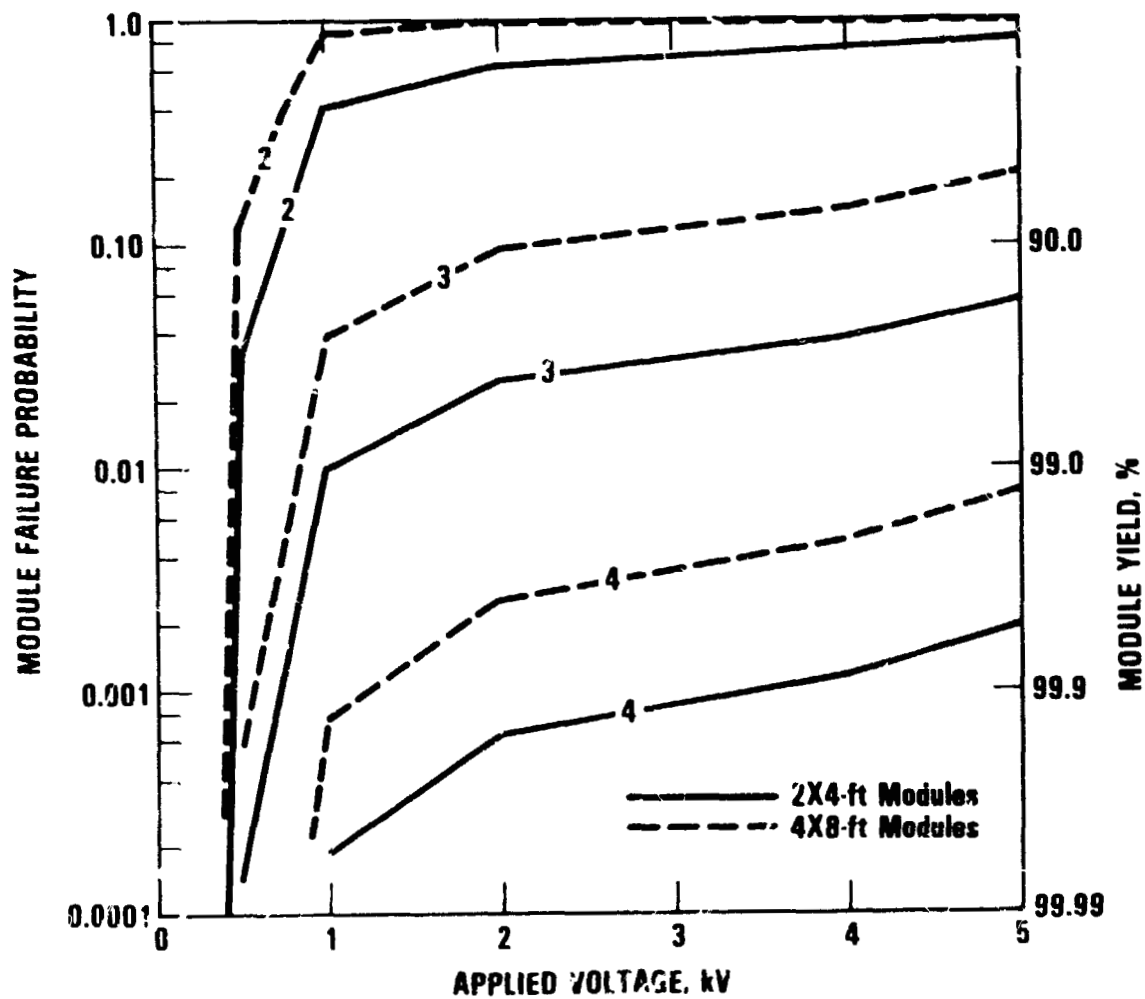


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Failure Probability of Modules Using Indicated
Number of Layers of 0.48-mil Mylar Insulating Film



Failure Probability of Modules Using Indicated
Number of Layers of 1.42-mil Mylar Insulating Film



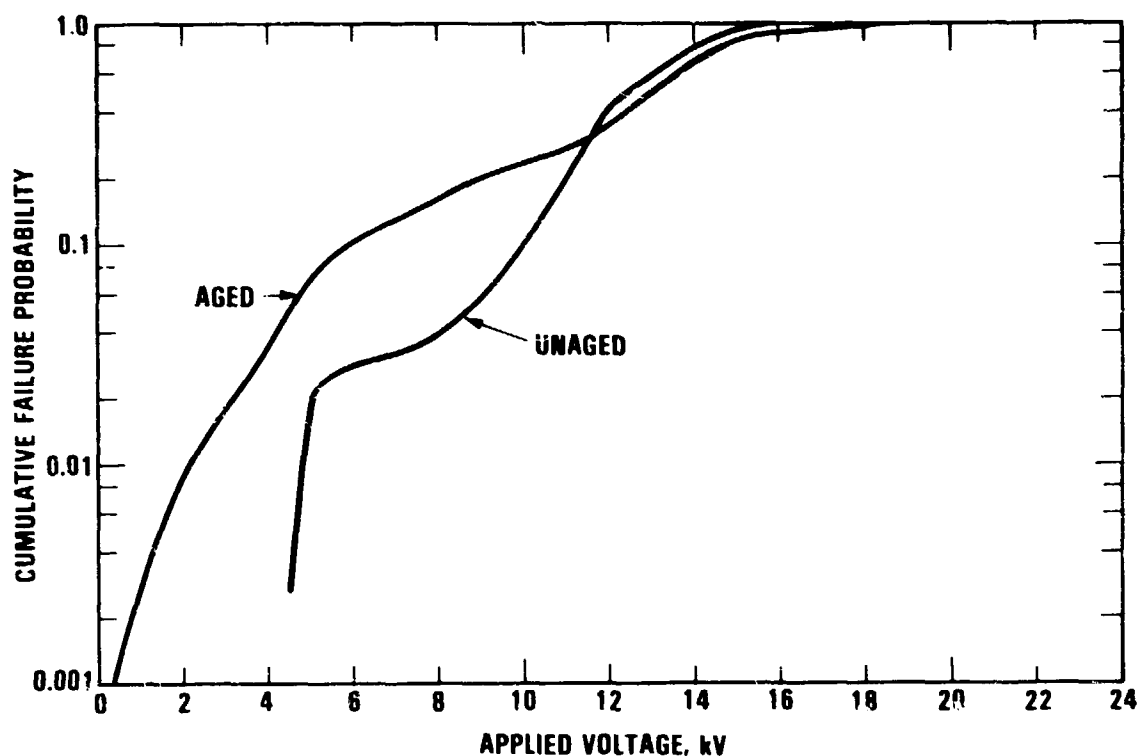
Conclusions From Multilayer Studies

- **Multilayer Mylar Films Perform Better Than Theoretically Expected, Perhaps Because of the Presence of Bonding Layers**
- **Minimum Life-Cycle Costing, in Conjunction With the Module Failure Probability Curves, Can Be Used to Determine the Least Number of Film Layers That Will Ensure Acceptable Hi-Pot Yields**
 - **Reference: G. Mon, "Defect Design of Insulation Systems for Photovoltaic Modules," 15th IEEE Photovoltaic Specialists Conference, pp. 964-971, 1981**
- **With Knowledge of How Environmental Exposure (Aging) Changes a Materials Voltage Breakdown Characteristics, These Same Design Tools Can Determine Dielectric Design to Yield Acceptable Module Performance Over the Life of the Array Field**

Aging Studies

- **Purpose:**
 - **To Ascertain Changes in Dielectric Voltage Breakdown Characteristics Resulting From Environmental Exposure**
 - **To Enable Realistic Prediction of 20-Year Failure Probabilities**
- **Aging Apparatus**
 - **HIVEC**
 - **Associated Humidity Chambers and Ovens**
- **Procedure**
 - **Break Down Selected Films Both Before and After Aging**

Voltage Breakdown Characteristics of 4.00-mil Experimental
White Tedlar: Unaged vs Aged (1704 h at 40°C/93% RH)



Conclusions Based Upon Aging Studies

- Preliminary Results Indicate That Environmental Exposure Can Significantly Alter Single-Layer, and Hence Module, Failure Probabilities
- Much Additional Testing Is Necessary Before Final Conclusions Can Be Made

Additional Test Results

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■ Encapsulants

● EVA

● EMA

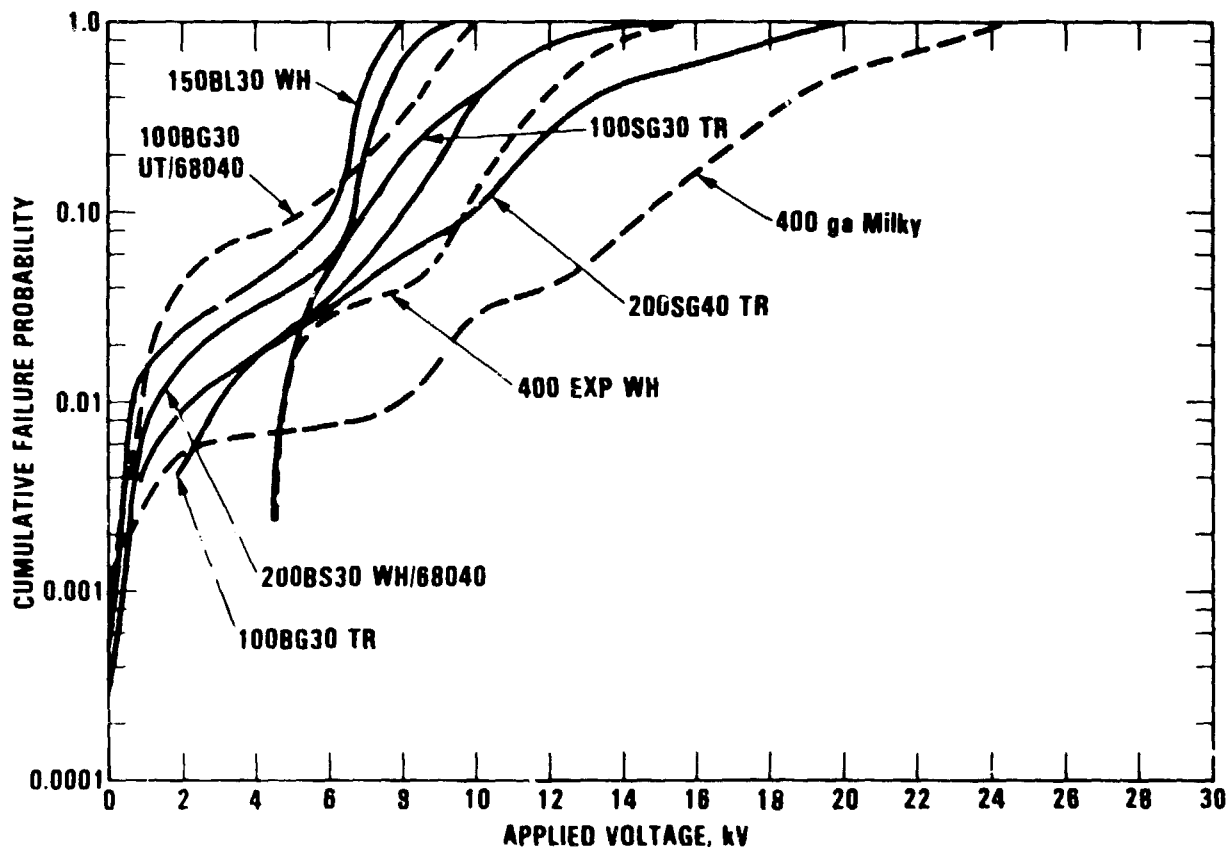
■ Back-Cover Films

● Tedlar

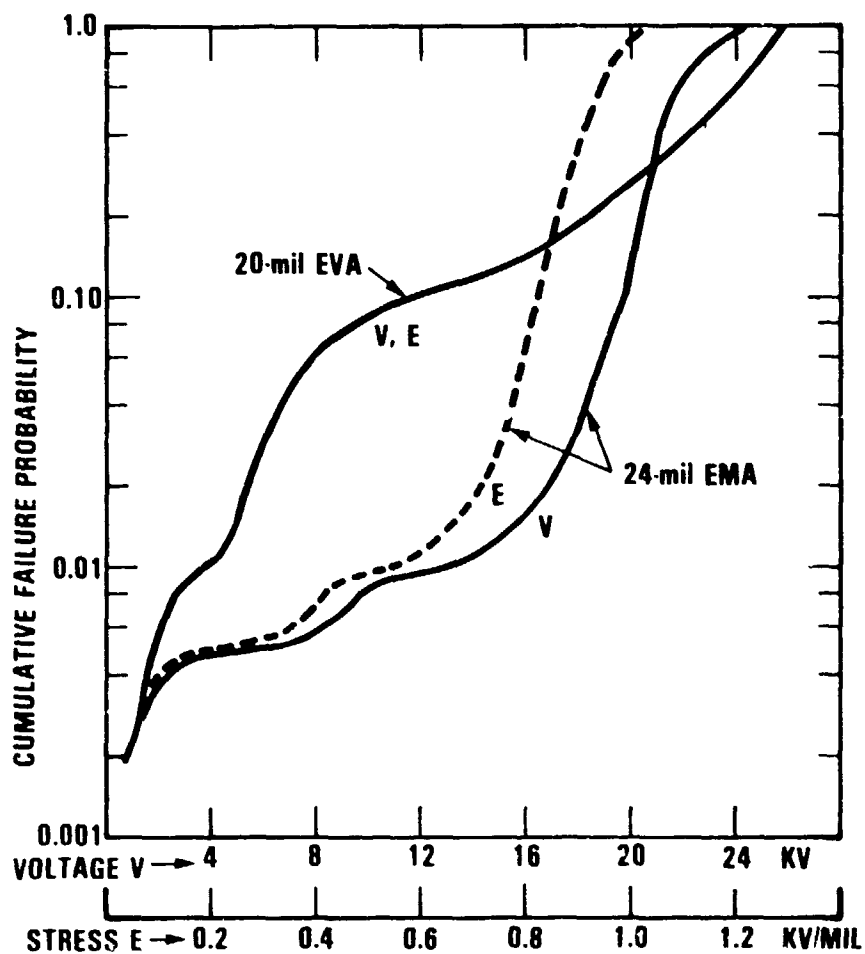
● Polyester

● Tedlar/Polyester/Aluminum/Tedlar

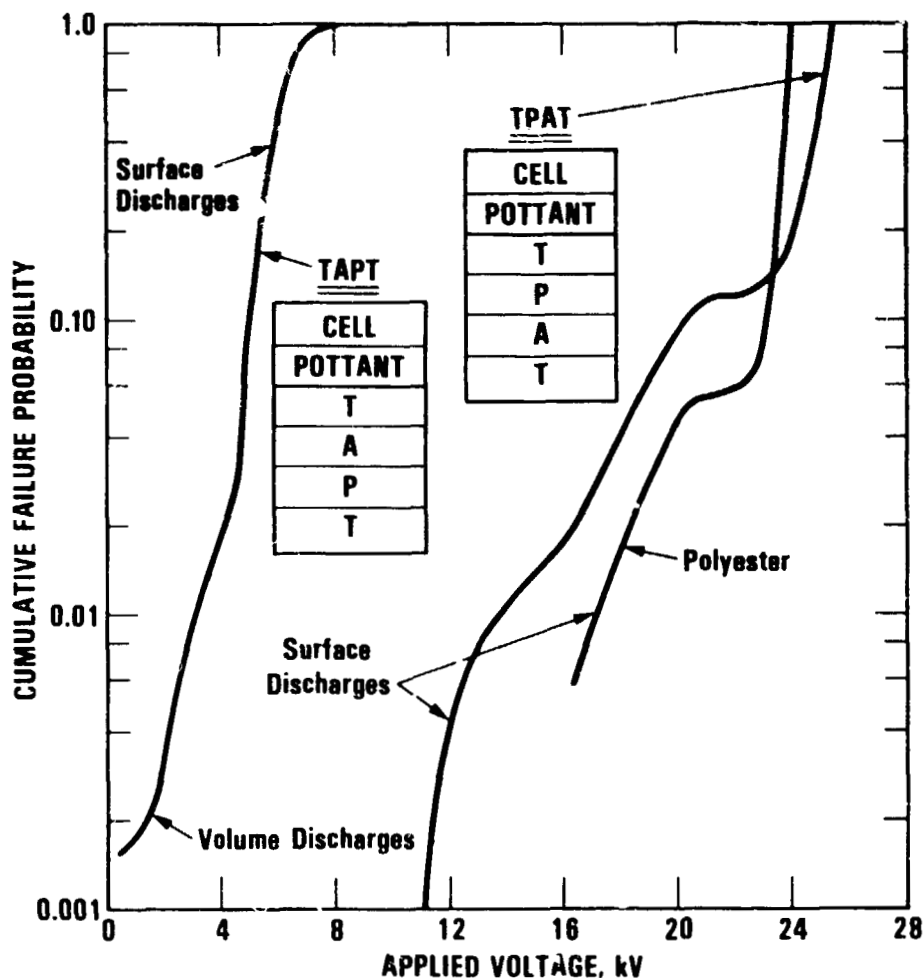
Voltage Breakdown Characteristics of Single-Layer Tedlar
Films (per Unit Test Area: $A_T = \pi/4 \text{ in}^2$)



Comparison of Voltage Breakdown Characteristics of EVA and EMA



Voltage Breakdown Characteristics of Tedlar/Polyester/Aluminum/Tedlar (1.50/4.0/0.7/1.5 mils)



Directions for Future Research

Continuation of Voltage Breakdown Characterization Program

- Test Composite Insulation Systems
- Develop Cost-Optimal Module Design Algorithms
Based Upon Voltage-Probability Data

Conduct Fundamental Degradation Studies of Photovoltaic Insulation Systems

- Partial Discharge (Corona)
- Pulse-Height Analysis
- Add ac/dc Test Equipment Can Measure Microscopic
Erosion of Dielectric; May Enable Long-Term Prediction of Module
Electrical Service Life Without Extensive Testing

LEAKAGE CURRENT IN ENCAPSULANTS

JET PROPULSION LABORATORY

A. Shumka

Objectives

- CHARACTERIZE THE LEAKAGE CURRENT BETWEEN CELLS AND A MODULE GROUND PLANE AS A FUNCTION OF VOLTAGE AND TEMPERATURE FOR ONE PARTICULAR TYPE OF COMMERCIALY USED ENCAPSULATION SYSTEM
- EVALUATE LEAKAGE CURRENT RESULTS IN TERMS OF CURRENT PROCUREMENT SPECIFICATION REQUIREMENTS
- INDICATE WHERE AN UPGRADING OF THESE SPECIFICATIONS MAY RESULT IN MODULE DESIGNS WITH IMPROVEMENTS IN LONG LIFE AND SAFETY

Module Procurement Specification for Leakage Current

- REQUIREMENT OF SPECIFICATION
 - ROOM TEMPERATURE LEAKAGE CURRENT NOT TO EXCEED $50 \mu\text{A}$ AT 2000 Vdc (HI-POT TEST)
- LIMITATION OF SPECIFICATION
 - TYPICAL NOCT FOR BLOCK IV MODULES RANGES FROM 50 TO 60 C
 - NO SPECIFICATION FOR LEAKAGE CURRENTS ABOVE ROOM TEMPERATURE
 - NO SPECIFICATION FOR MAXIMUM ALLOWABLE TEMPERATURE COEFFICIENT FOR LEAKAGE CURRENT

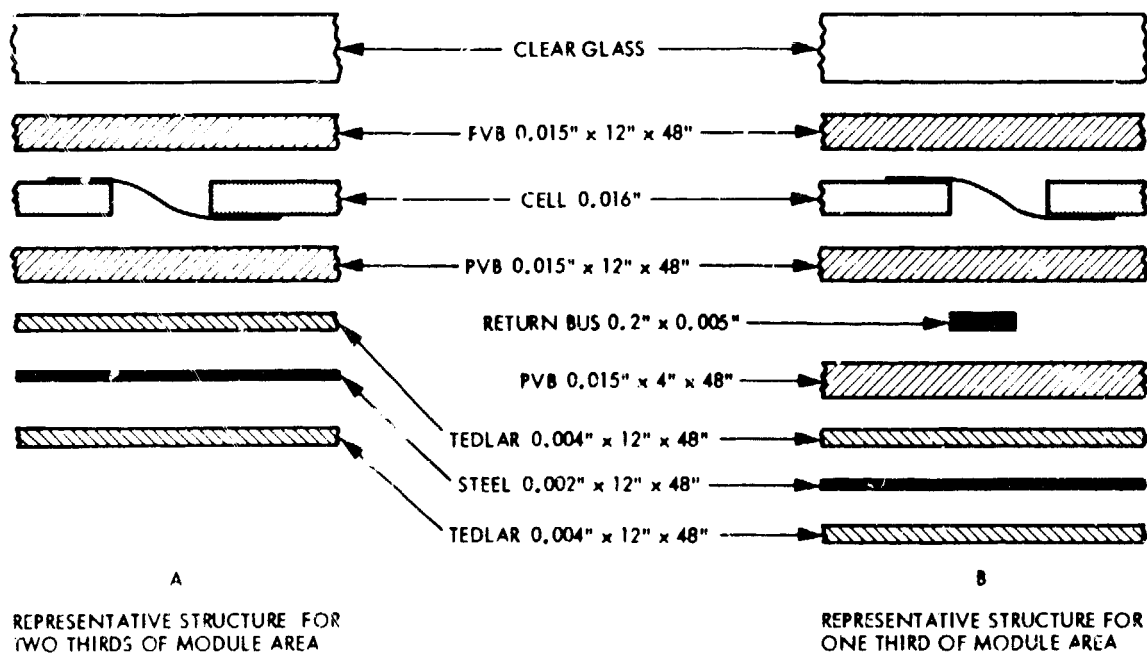
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MODULE PERFORMANCE AND FAILURE ANALYSIS AREA

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Test Approach

- SELECTED THREE BLOCK IV MODULES OF SAME DESIGN AND MANUFACTURE - ONE OF WHICH HAD A REPORTED TEMPERATURE SENSITIVE LEAKAGE CURRENT
- MEASURE CAPACITANCE AND DISSIPATION FACTOR AT ROOM TEMPERATURE
- MEASURE PARTIAL DISCHARGE (CORONA) BREAKDOWN VOLTAGE AT ROOM TEMPERATURE
- MEASURE AND CHARACTERIZE MODULE LEAKAGE CURRENTS AT SEVEN DIFFERENT VOLTAGES (100, 200, 500, 1000, 1500, AND 2000 Vdc) AND AT SEVEN TEMPERATURES (24, 35, 45, 55, 65, 75 AND 85C)

Exploded View of Module Structure



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Capacitance Dissipation Factor at Room Ambient, 1 kHz

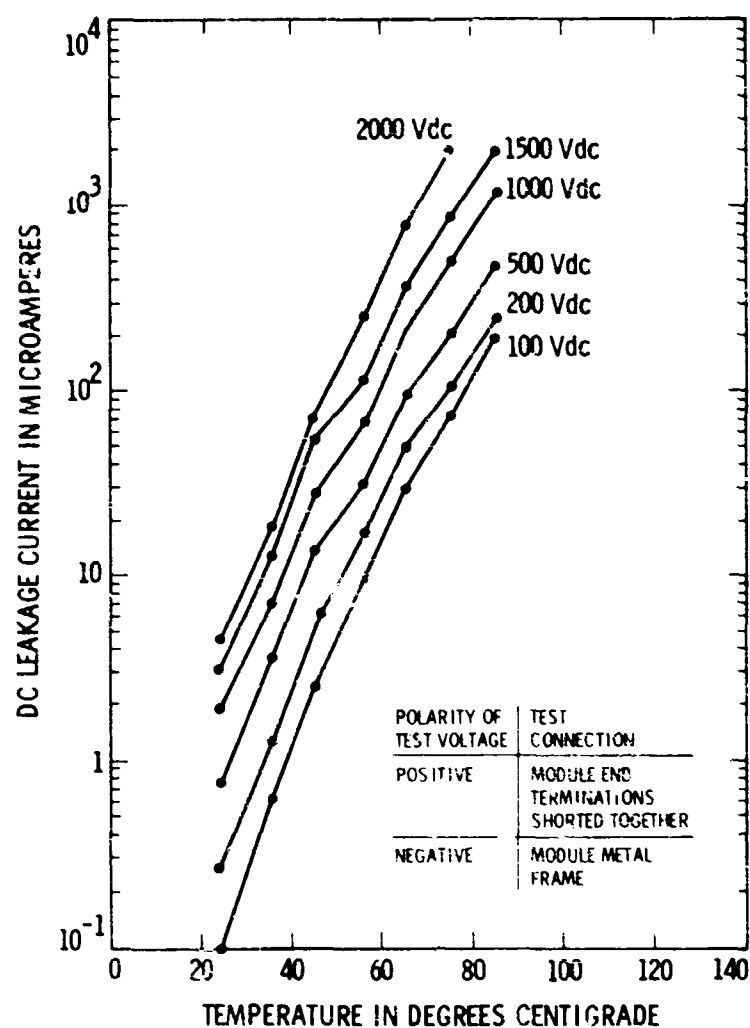
MODULE S/N	CAPACITANCE VALUE IN (μ F)	DISSIPATION FACTOR VALUE IN (%)	REMARKS
1	0.02231	5.30	SUBJECT MODULE RETURNED FROM HAWAII
2	0.02149	4.95	COMPARISON MODULE JPL SPARE
3	0.01976	4.60	COMPARISON MODULE JPL SPARE

Partial Discharge (Corona) at Room Ambient, 60 Hz

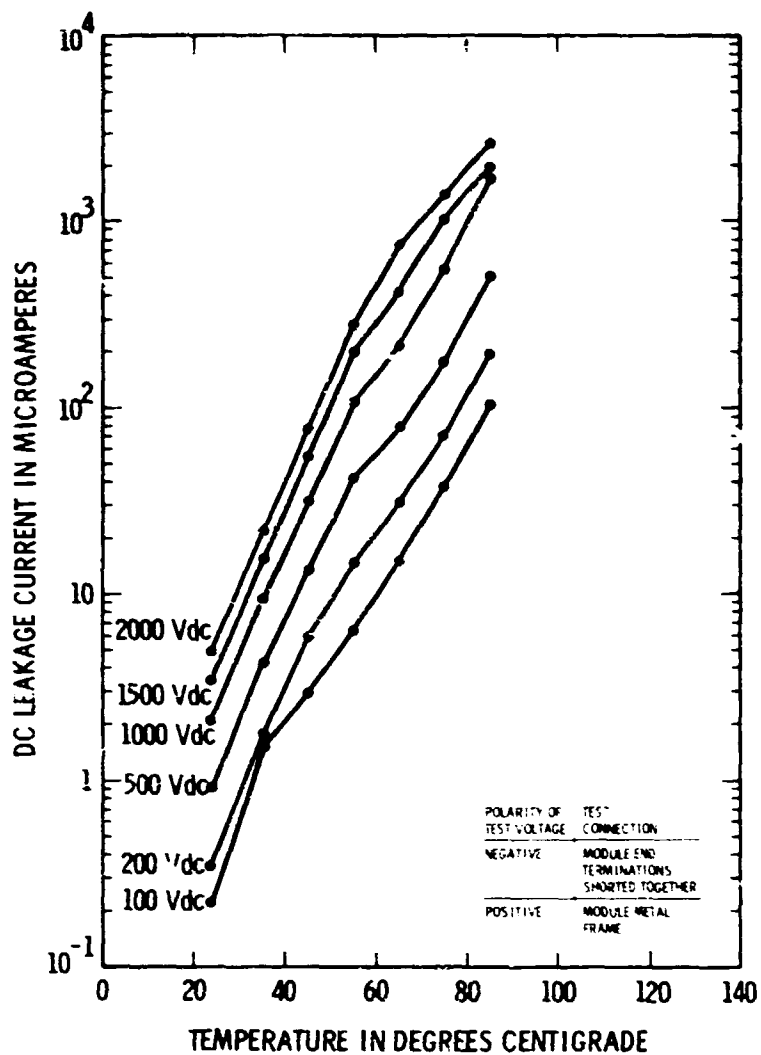
MODULE S/N	PARTIAL DISCHARGE "INCEPTION" LEVEL		PARTIAL DISCHARGE AT 100 pC LEVEL		REMARKS
	(pC)	TEST VOLTS (KV PEAK)	(pC)	TEST VOLTS	
1	20	6.6	124	7.9	MODULE RETURNED FROM HAWAII
2	22	5.8	103	6.3	COMPARISON MODULE - JPL SPARE
3	23	4.4	105	5.1	COMPARISON MODULE - JPL SPARE

NOTE: THE 100 pC LEVEL OF PARTIAL DISCHARGE IS EQUIVALENT TO $\approx 10 \mu$ A
AVERAGE CURRENT.

DC Leakage Current Test Results vs Temperature
and Voltage: Module No. 1



DC Leakage Current Test Results vs Temperature
and Voltage: Module No. 1



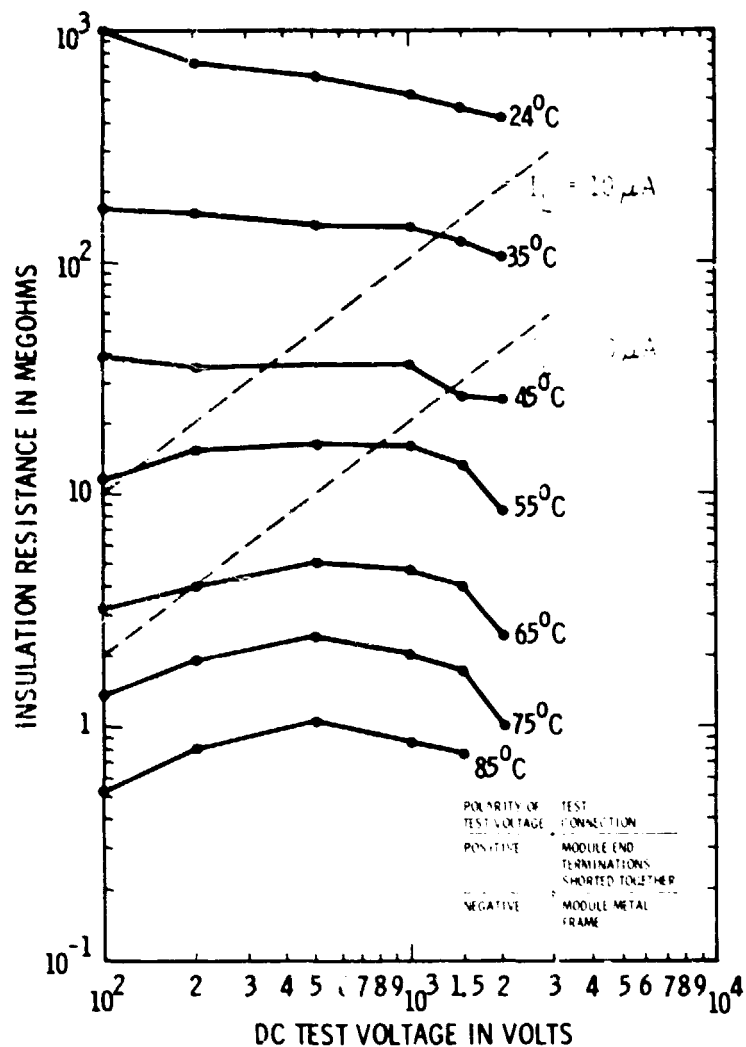
Voltage as a Function of Temperature
for a 50 μ A Leakage Current

VOLTAGE (VOLTS)	MODULE TEMPERATURE (DEG C) FOR A 50 μ A DC LEAKAGE CURRENT					
	MODULE #1 WITH TERMINAL POLARITY		MODULE #2 WITH TERMINAL POLARITY		MODULE #3 WITH TERMINAL POLARITY	
	+	-	+	-	+	-
2000	42	42	40	40	41	40.5
1500	44	44.5	42.5	42	45	46
1000	52	49.5	47	47	52.5	55
500	59.5	58	56	59.5	59.5	62.5
200	65	71	62.5	69.5	68	72
100	71	77.5	69	76.5	74	79

+ POLARITY - MODULE FRAME CONNECTED TO GROUND

- POLARITY - TERMINALS CONNECTED TO GROUND

Insulation Resistance Test Results vs Temperature and Voltage: Module No. 1



Conclusions

- LEAKAGE CURRENT IN THE ENCAPSULATION SYSTEM TESTED - PVB/TEDLAR - EXHIBITED A VERY STRONG DEPENDENCE ON TEMPERATURE AND MAY REPRESENT POTENTIAL LONG TERM PROBLEMS
- NEED TO SIMILARLY CHARACTERIZE OTHER ENCAPSULATION SYSTEMS
- NEED TO UNDERSTAND CONDUCTION MECHANISM IN TERMS OF TIME AND TEMPERATURE. THIS MAY PROVIDE INFORMATION IMPORTANT FOR QUALITY CONTROL
- NEED TO DETERMINE EFFECT OF LEAKAGE CURRENT ON LONG TERM LIFE
- NEED TO REVIEW EFFICACY OF BLOCK IV LEAKAGE CURRENT SPECIFICATION - $<50 \mu\text{A}$ AT 2000 V_{dc} AT ROOM TEMPERATURE
- NEED TO ESTABLISH SPECIFICATIONS FOR ACCEPTABLE LEVELS OF LEAKAGE CURRENT FOR LONG TERM RELIABILITY AND SAFETY

CELL RELIABILITY TESTING

CLEMSON UNIVERSITY

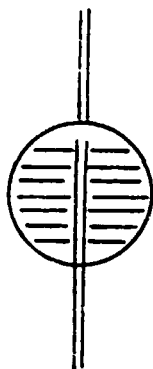
J.W. Lathrop

Accelerated Stress Tests

FORM

TEST

LIMIT



UNENCAPSULATED

BIAS-TEMPERATURE

PRESSURE COOKER

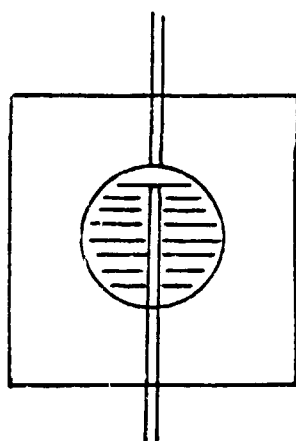
85°C/85% RH

THERMAL CYCLE

SOLDER MELTING

$T < 175^{\circ}\text{C}$

THERMAL SHOCK



ENCAPSULATED

85°C/85% RH

THERMAL CYCLE

ENVIRONMENTAL

ORGANIC DECOMPOSITION

$T < 95^{\circ}\text{C}$

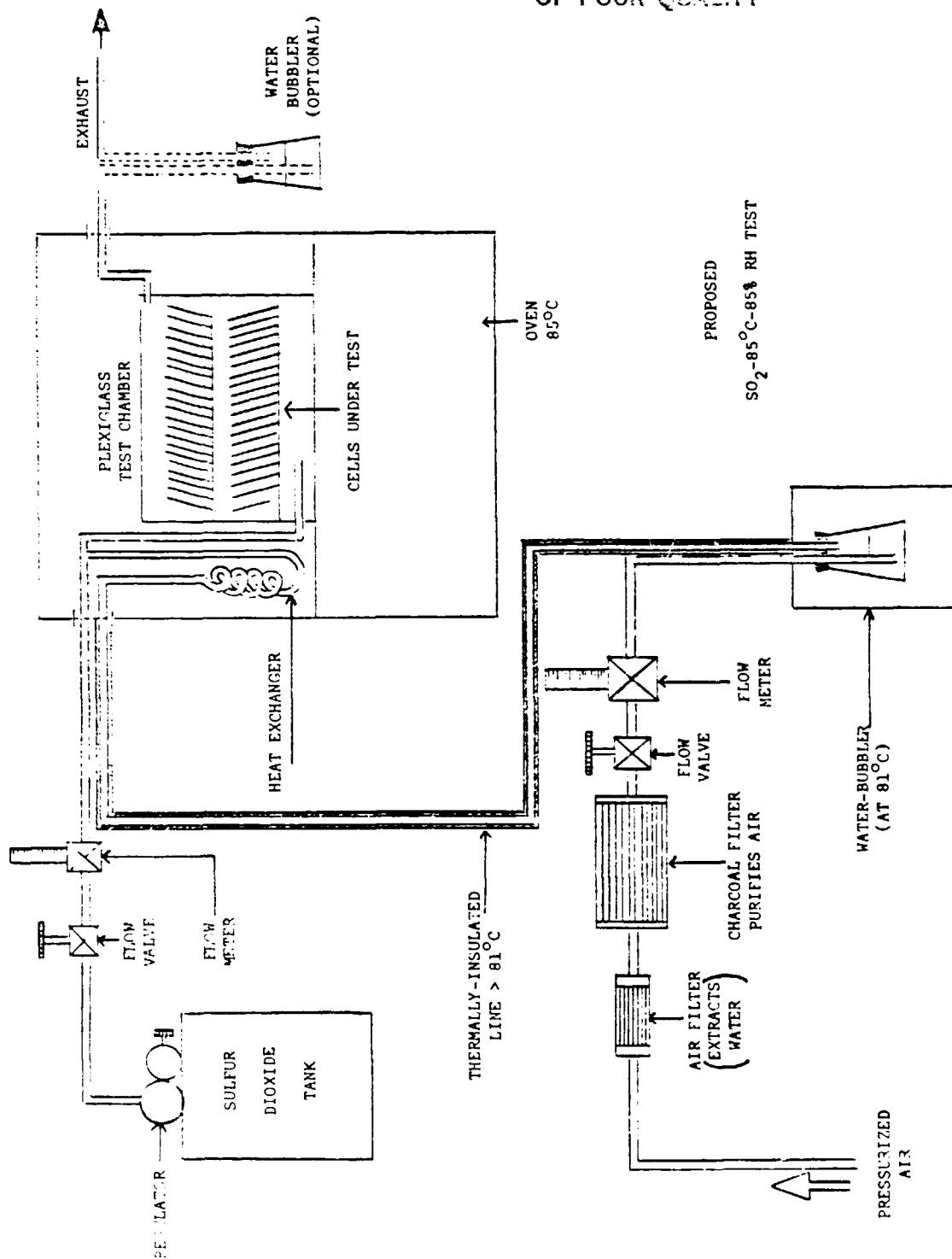
Anticipated Failure Mechanisms

PHYSICAL PHENOMENON	OBSERVED EFFECT	ACCELERATING TEST
DIFFUSION	LOSS OF COLLECTION EFFICIENCY	
	BULK RESISTIVITY INCREASE	B-T
	CONTACT RESISTANCE INCREASE	
CORROSION	METAL REMOVAL	PC
	METAL PLATING	85/85
	AR COATING REMOVAL	
DIFFERENTIAL EXPANSION	METAL PEELING	
	CELL FRACTURE	TC/TS

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Proposed $\text{SO}_2 - 85^\circ\text{C} - 85\% \text{ RH}$ Test



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Modules for Encapsulated Cell Testing

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CELL METALLIZATION SYSTEMS

	Ni-SOLDER 7 TYPES		Cu PLATE 2 TYPES		Ag SCREEN 1 TYPE			
	S	M	S	M	S	M		
G/EVA/G	12	50	2		3			
G/EVA/T	18	50	2	24	3			
G/EMA/T	18	50	2		3			
G/EVA/F	15		5	50	3			
T/EVA/S	15		2		3			
G/EVA				25				
G/SR/G	<u>12</u>		<u> </u>		<u> </u>			
	78	162	13	99	15		106	261
	240		112		15		367	

S - SPRINGBORN FABRICATED

M - MANUFACTURER FABRICATED

LONG-TERM MODULE TESTING AT WYLE LABORATORIES

JET PROPULSION LABORATORY

D.H. Otth

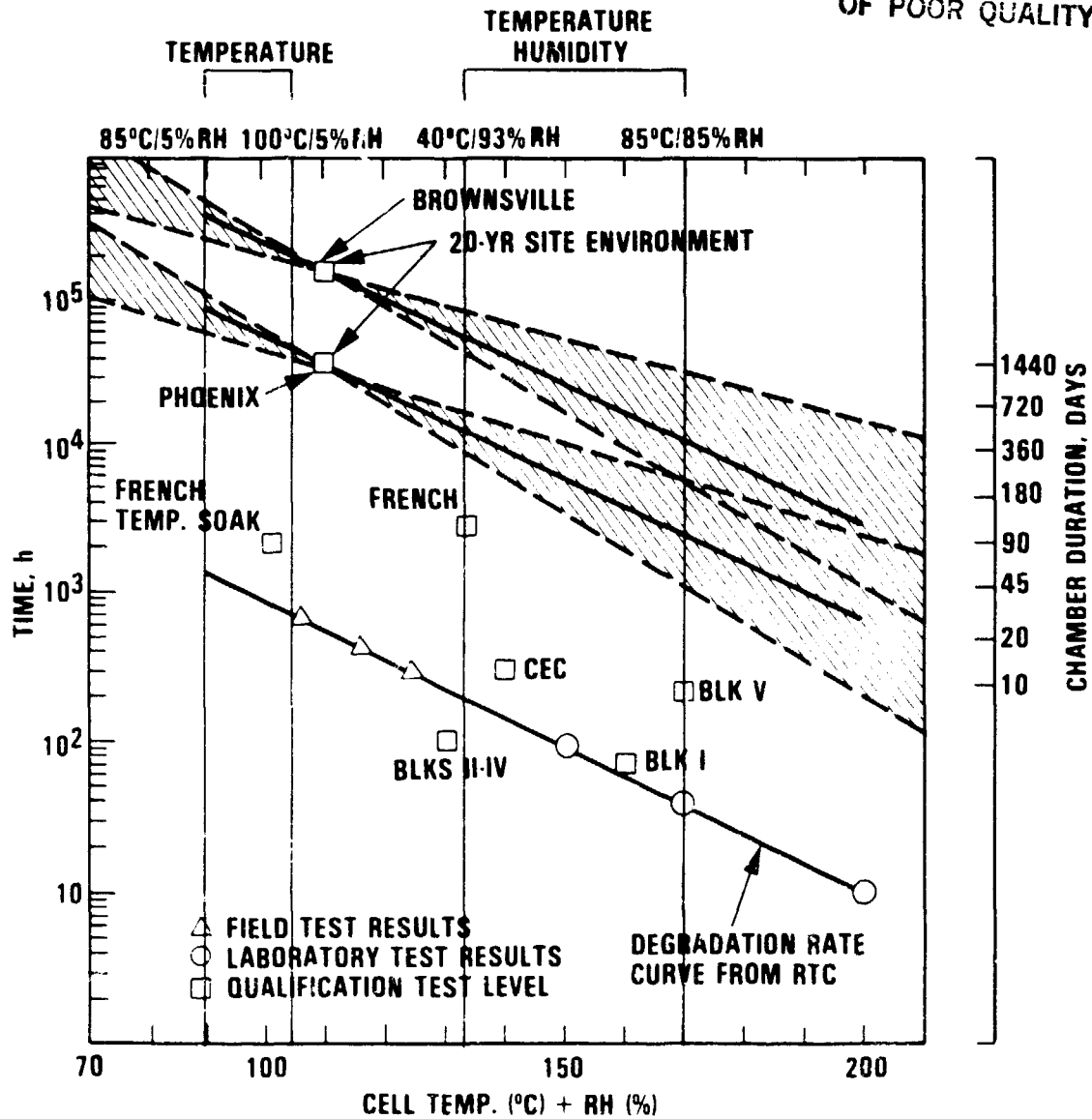
Objectives

- **Understand Temperature/Humidity-Bias Failure Mechanisms of Typical Photovoltaic Modules and Materials**
 - **Cells, Encapsulants, Interconnects**
 - **Back Covers, Edge Seals**
- **Establish Generic Functional Relationships Among Temperature, Humidity, Bias and Time for Observed Failure Mechanisms**
- **Determine Relative Lifetimes of Roof-Mounted vs Ground-Mounted Arrays**
- **Understand Relative Severity (Acceleration Factor) of Candidate T/H-B Qualification Tests and Define Recommended Levels**

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Long-Term Module Testing

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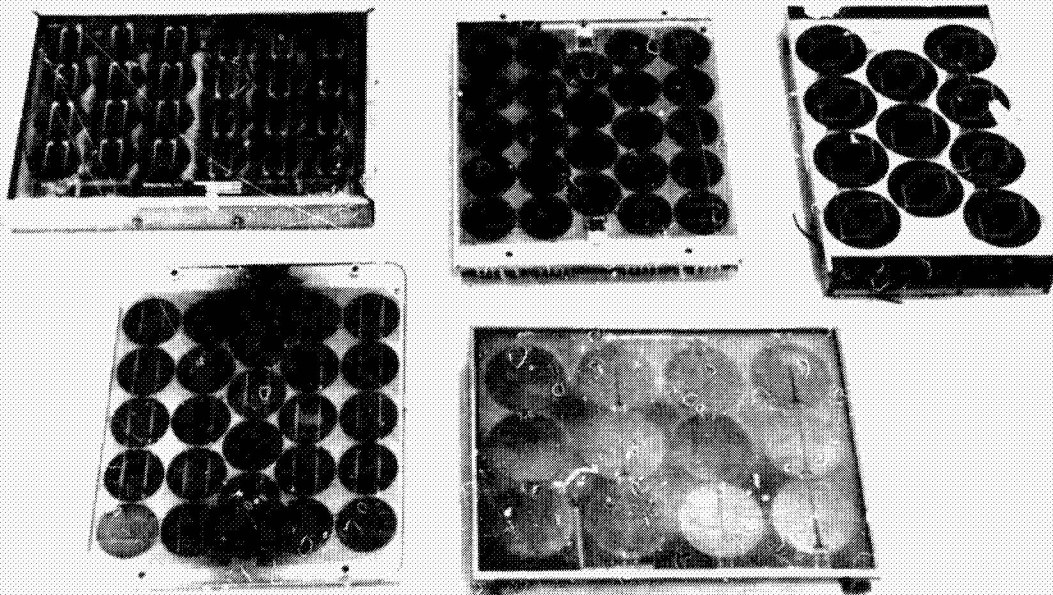
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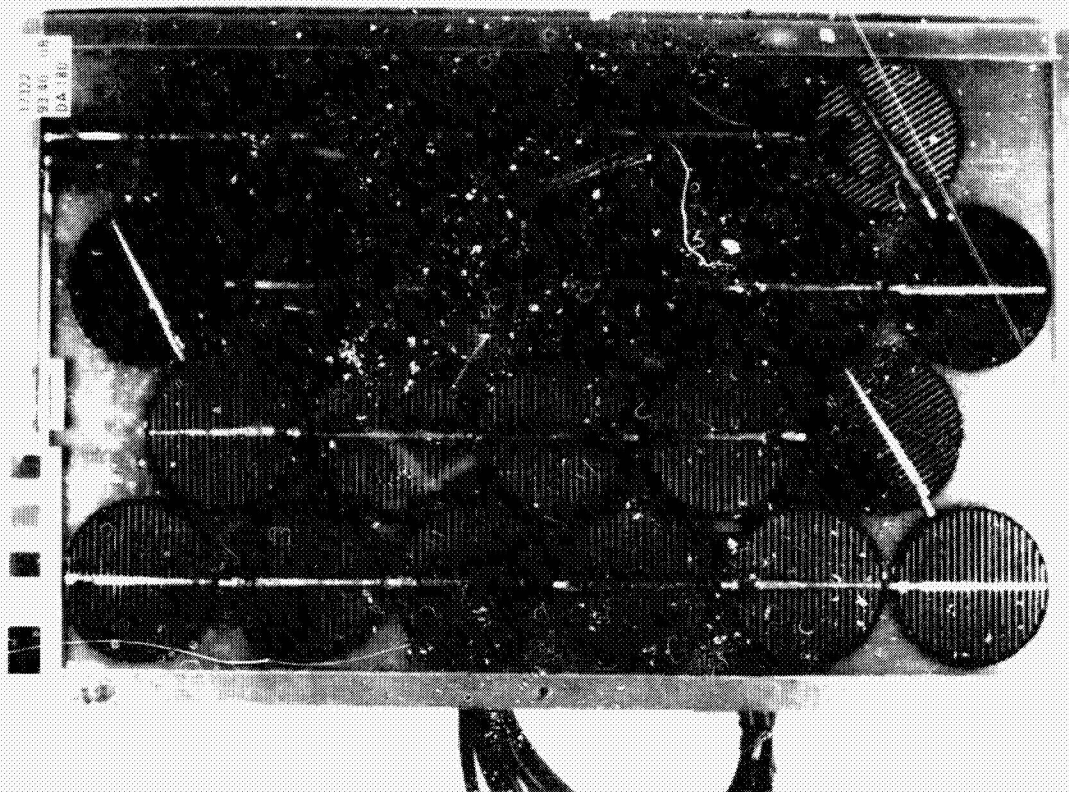
Module Materials

- Encapsulants
Silicone, RTV, PVB, EVA
- Cell Metallization
Ni-Solder, Ti-Pd-Ag, Print Ag, Pd-Ni-Solder
- Cell Types
Semi-XTL, Silicon (p/n, n/p)
- Substrate/Superstrate Structure
Glass, FRP, Aluminum
- Back Covers
Tedlar, Mylar, Tedlar-Fe-Tedlar, Tedlar-Al-Tedlar
- Frames
Al, Stainless Steel

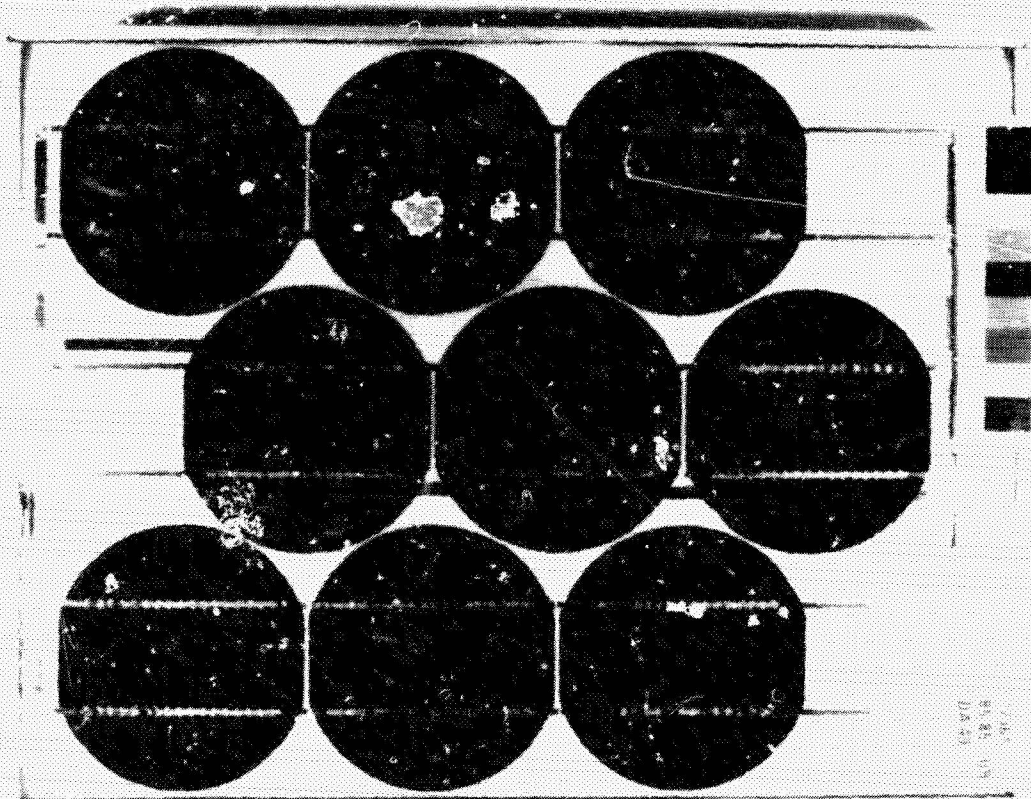
Blocks II and III Modules in Wyle Testing



Block I Type Module in Wyle Testing

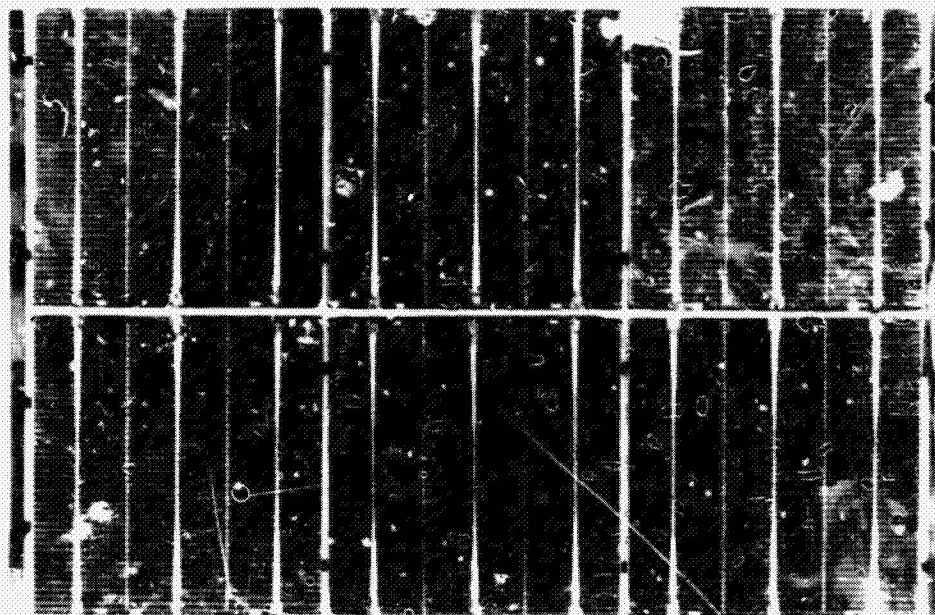


Block IV Modules in Wyle Testing



Block IV Minimodule With Semicrystalline Cells

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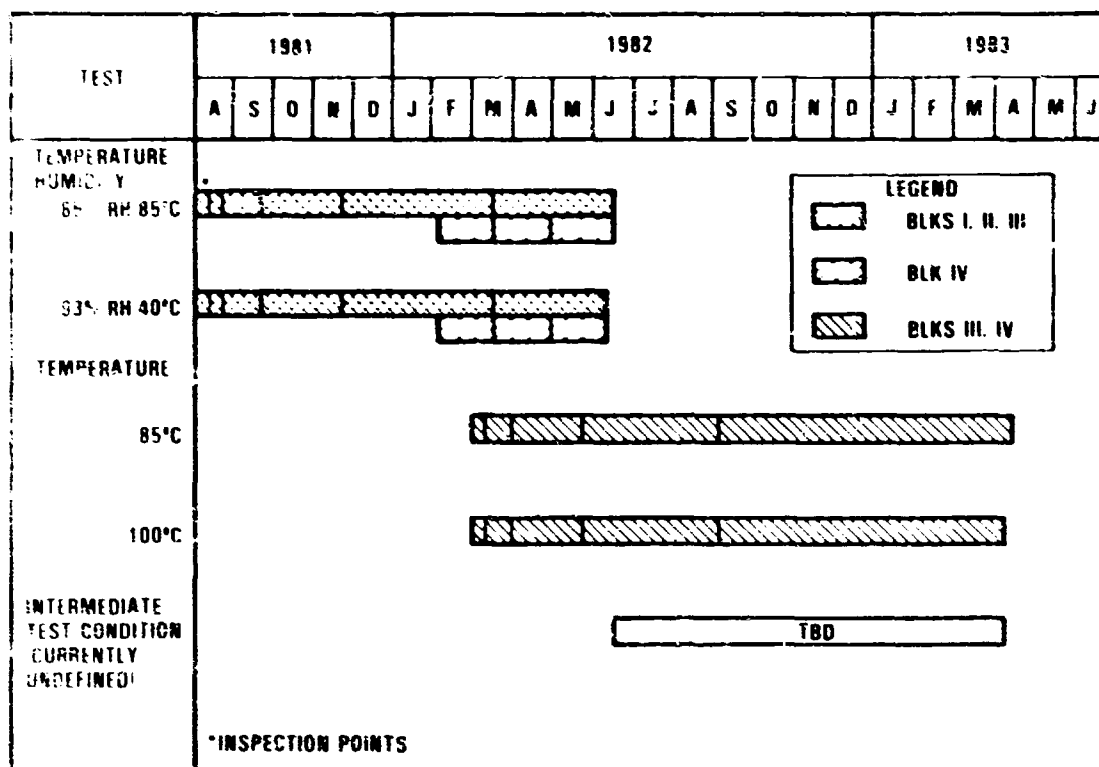


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85-81-1-6
8A-49

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Schedule



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OF POOR QUALITY

Visual Degradation Mechanisms

		95°C/85% RH					40°C/93% RH					BIAS
		DAYS					DAYS					
		10	20	45	90	180	10	20	45	90	180	
ENCAPSULANTS												
SILICONE/RTV	DISCOLORATION											
	DELAM											
PVB	DISCOLORATION											
	DELAM											
EVA	DISCOLORATION											
	DELAM											
METALIZATION												
PRINT Ag	GRID YELLOW											INCR
	GRID CORROSION											INCR
Ni SOLDER												
Ti-Pd-Ag												
Pd-Ni-SOLDER												
SUBSTRATE/BACKCOVER												
FRP	DISCOLORATION											
	EMBRITTLEMENT											
MYLAR												
TEDLAR												
BUS BAR/INTERCONNECTS												
SEALS	CORROSION											
	DIFFUSION											INCR

(40/93)

PRELIMINAR . LONG-TERM TESTING RESULTS

JET PROPULSION LABORATORY

G.R. Mon

Presentation Outline

- **VISUAL OBSERVATIONS**
 - **ROAD MAPS**
 - **PHOTOGRAPHS**
- **ELECTRICAL MEASUREMENTS**
 - **I-V CURVE**
 - **INSULATION (DIELECTRIC) DATA**
- **DATA INTERPRETATION**
 - **IDENTIFICATION OF DEGRADATION MECHANISMS**
 - **QUANTIFICATION OF DEGRADATION RATES**
 - **COMPARISON OF RESULTS WITH RESULTS FROM OTHER LABORATORY TESTS AND FIELD EXPERIENCE**

Visual Observations From Long-Duration Module Tests (112 Days)

GENERIC MODULE TYPE	VISUAL OBSERVATIONS	
	85/85	93/40
GLASS/PVB/MYLAR Ag PASTE	DISCOLORATION: PVB CORROSION: CIRCUITRY GRID LINES	
RTV/ALUMINUM No SOLDER	DISCOLORATION: RTV MICROCRACKS: RTV	SLIGHT DISCOLORATION: RTV
GLASS/RTV/ALUMINUM No SOLDER	DISCOLORATION: RTV DELAMINATION AT TERMINALS	SLIGHT DISCOLORATION: RTV
GLASS/PVB/TEDLAR Ag PASTE	DISCOLORATION: PVB CORROSION: CIRCUITRY GRID LINES	DISCOLORATION: GRID LINES DELAMINATION: EDGE SEAL
GLASS FIBER RTV REINFORCED POLYESTER Ti Pd Ag	DISCOLORATION: SUBSTRATE CORROSION: CIRCUITRY	SLIGHT CORROSION: CIRCUITRY
RTV/GLASS FIBER No SOLDER	DISCOLORATION: SUBSTRATE SLIGHT CORROSION: CIRCUITRY	

Electrical Measurements

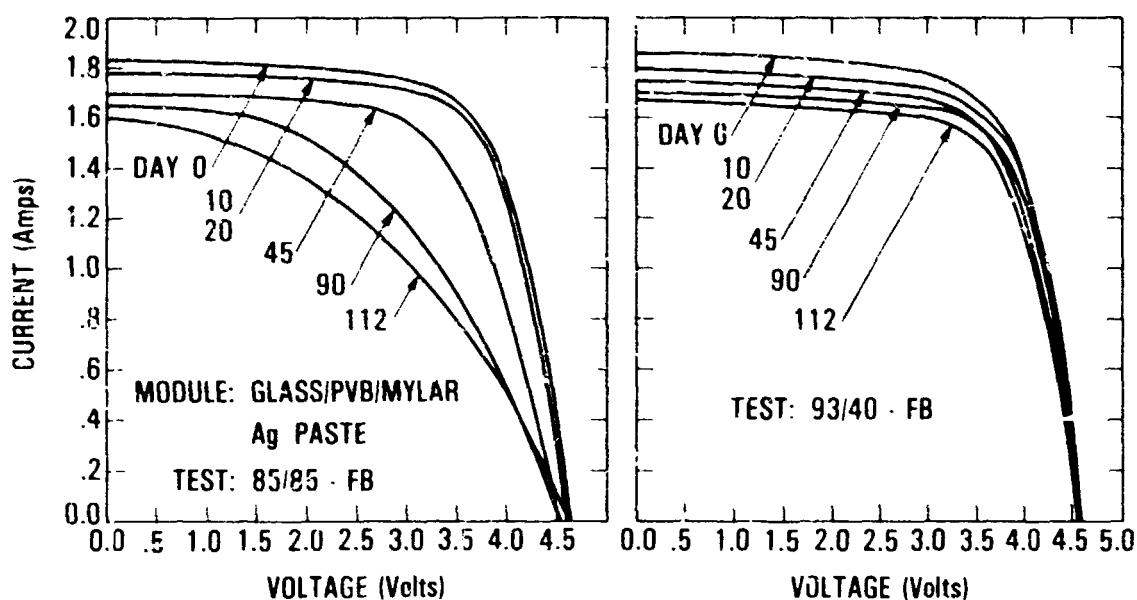
• I-V CURVE DATA

- V_{oc}
- I_{sc}
- P_{mp}
- V_{mp}
- I_{mp}

• DIELECTRIC DATA

- R_{INSUL}
- C_{INSUL}
- $\tan \delta$

Example I-V Curve Results (85/85 vs 93/40)



Summary of I-V Curve Findings (112 Days)

GENERIC MODULE TYPE	$\Delta I_{sc} \%$		$\Delta R_s \%$		$\Delta P_{mp} \%$	
	85/85	93/40	85/85	93/40	85/85	93/40
GLASS/PVB/MYLAR Ag PASTE	-5	0	+300	+10	-40	1
PTV/ALUMINUM Ni SOLDER	-2.5	0	+20	0	-2.5	1
GLASS/PTV/ALUMINUM Ni SOLDER	0	0	0	0	0	1
GLASS/PVB/TEFLAR Ag PASTE	-5	0	+60	+10	-20	1
RTV/GLASS FIBER REINFORCED POLYESTER Ti-Pd-Ag	-4	0	+100	+10	-15	1
RTV/GLASS FIBER Ni SOLDER	-3	0	+100	—	-20	1
	$I_{sc} \downarrow$		$R_s \uparrow$		$P_{mp} \downarrow$	

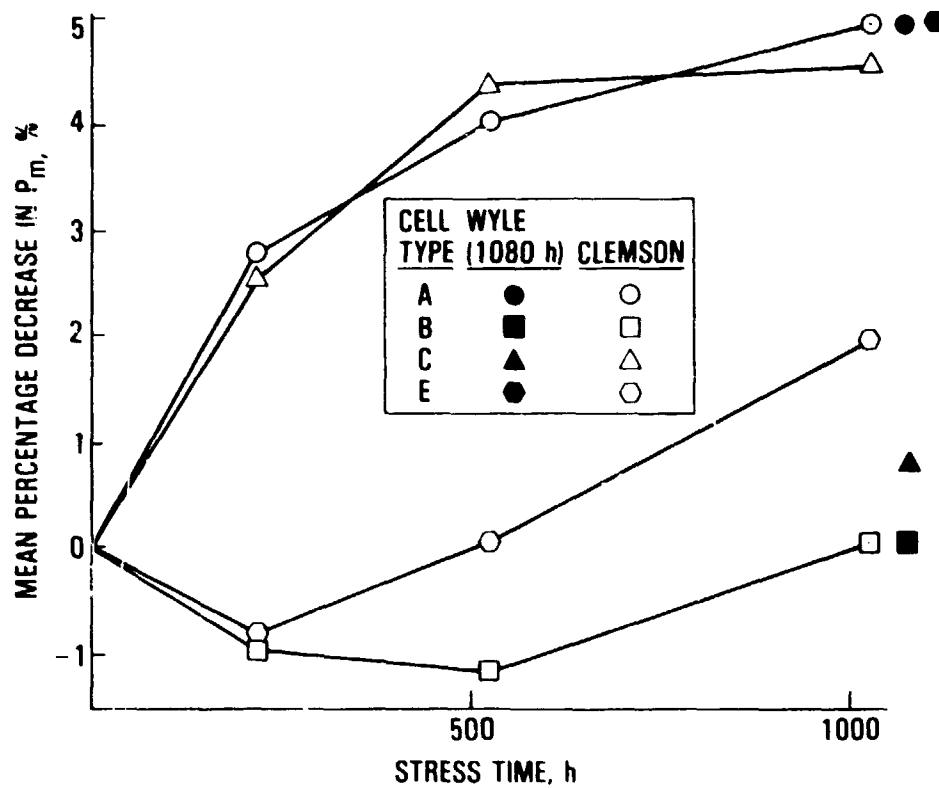
• AFTER SUBTRACTING THE CONTRIBUTION DUE TO I_{sc} LOSS, THE POWER LOSS RATE IS FOUND TO BE ROUGHLY ONE TENTH THE RATE OF SERIES RESISTANCE INCREASE.

Comparison Overview of Wyle and Clemson Tests

TEST SPECIMENS:		<u>WYLE</u>		<u>CLEMSON</u>	
		MINIMODULES		UNENCAPSULATED CELLS	
TESTS:		65/85 - FB		85/85 - FB	
		85/85 - UB		85/85 - UB	
		93/40 - FB		15 psig STEAM/121 - FB	
		93/40 - UB		15 psig STEAM/121 - UB	
GENERIC MODULE TYPE	CLEMSON CELL TYPE				
GLASS/PVB/MYLAR Ag PASTE					
RTV/ALUMINUM Ni SOLDER	C	0/85 - FB		0/75 - FB	
		0/85 - UB		0/75 - UB	
GLASS/RTV/ALUMINUM Ni SOLDER	C	0/100 - FB		0/135 - FB	
		0/100 - UB		0/135 - UB	
GLASS/PVB/ETD/LAR Ag PASTE	E			0/150 - FB	
				0/150 - UB	
GLASS FIBER RTV REINFORCED POLYESTER	B			0/165 - FB	
Ti/Pd Ag				0/165 - UB	
RTV/GLASS FIBER Ni SOLDER	A				

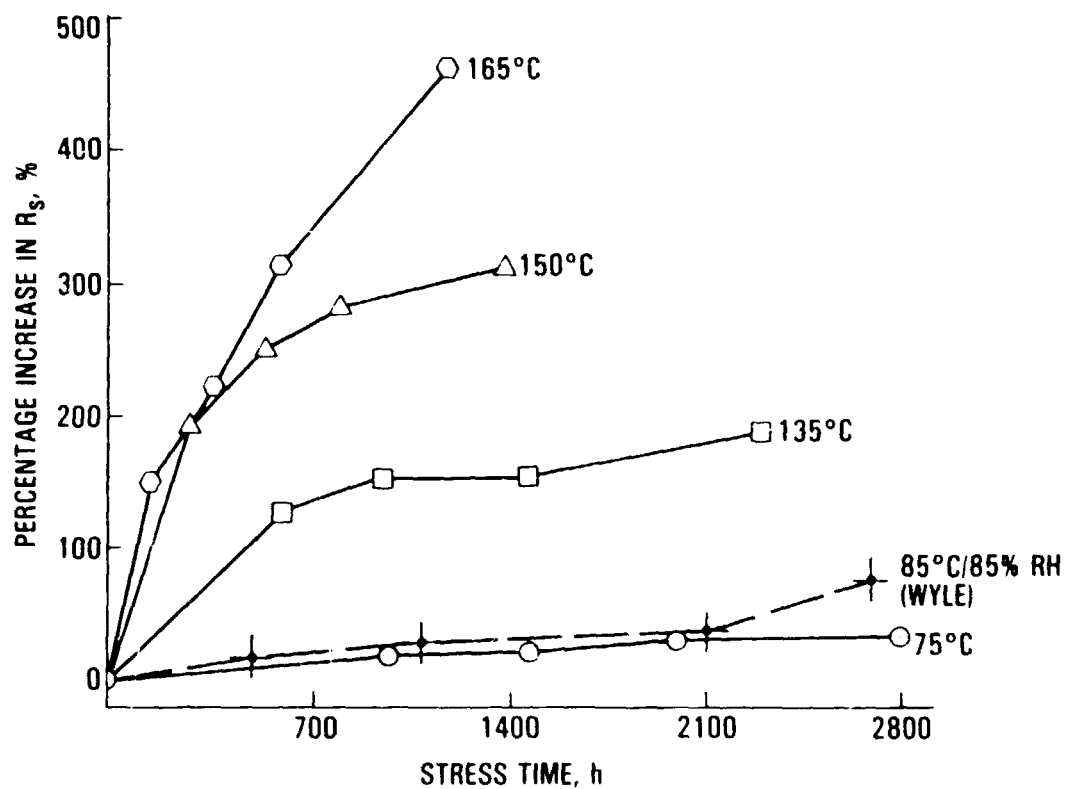
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Mean Percentage Decrease in P_m vs Stress Time
(85°C/85% RH Test)



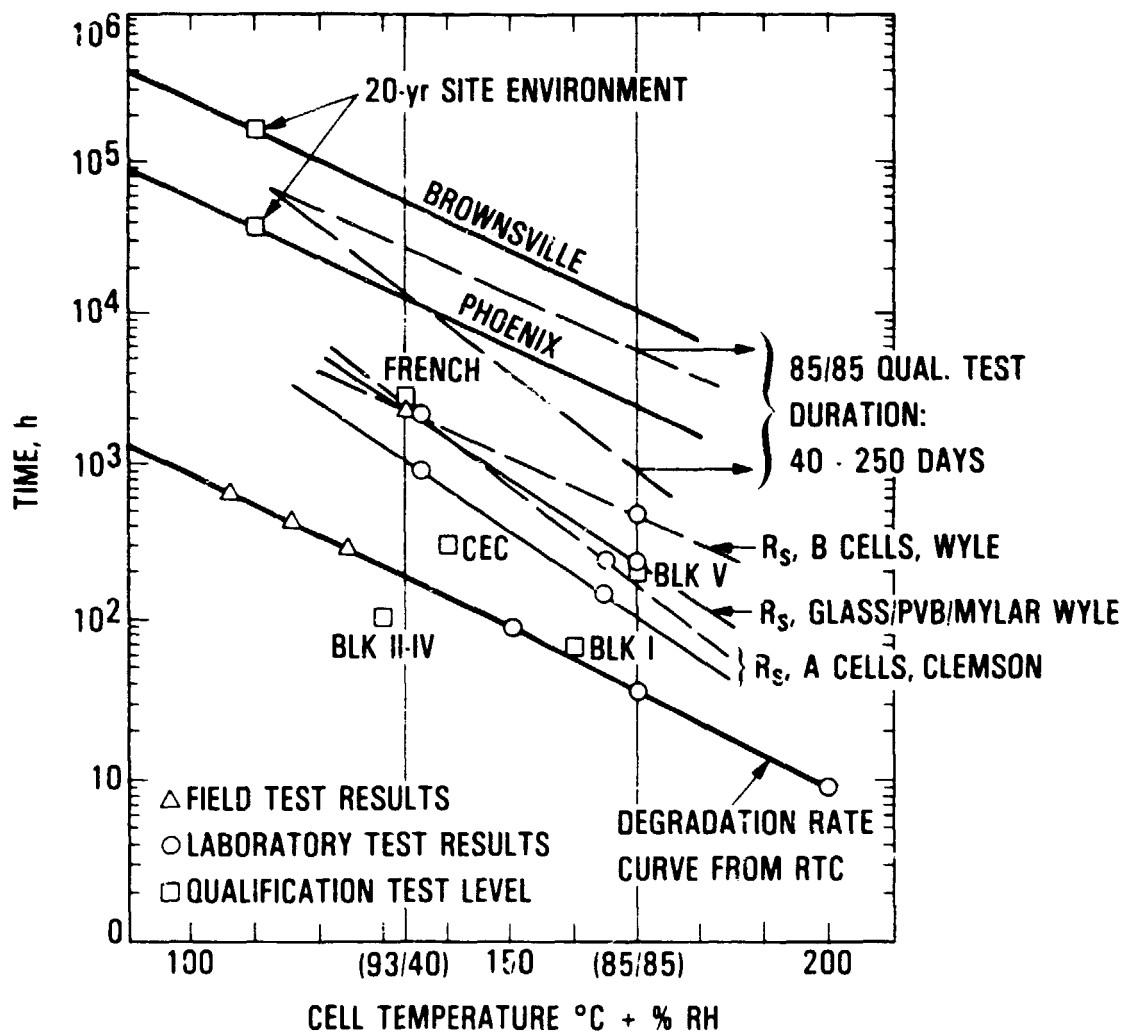
GRAPH OF
OF POWER

Behavior of R_s With B-T Stress Time: Typical Type A Cells



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Acceleration of Humidity and Temperature



OF PERFORMANCE

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Wyle-Clemson Test Comparisons: Conclusions

- **SERIES RESISTANCE INCREASES ARE COMPARABLE IN THE WYLE AND CLEMSON TESTS**
- **THE MAXIMUM POWER LOSSES DUE TO I_{sc} DECREASE AND R_s INCREASE ARE SEPARATELY DETERMINABLE**
- **IGNORING SHUNT, RESISTANCE EFFECTS, THE RATE OF R_s INCREASE IS APPROXIMATELY TEN TIMES THE RATE OF ASSOCIATED P_m DECREASE**
- **ACCELERATION CURVES SUGGEST THAT, BASED UPON DEGRADATION OF SERIES RESISTANCE, THE FRENCH AND THE BLOCK V QUALIFICATION TESTS ARE EQUIVALENT**
- **85/85 TEST CONDITIONS REQUIRE 40-250 DAYS OF OPERATION TO QUALIFY MODULES FOR 20-YEAR FIELD SERVICE**
- **ALL RESULTS ARE PRELIMINARY. ADDITIONAL TESTING AND ANALYSIS IS NECESSARY TO ESTABLISH:**
 - **PRECISE DEGRADATION MECHANISMS AND RATES**
 - **RELIABLE HUMIDITY/TEMPERATURE BIAS QUALIFICATION TEST PARAMETERS**

**ENGINEERING SCIENCES AREA
MODULE PERFORMANCE AND FAILURE ANALYSIS AREA**

Research Plans

- **ADDITIONAL TESTING**
 - **LONGER DURATION 93/40**
 - **CONTINUE TEMPERATURE-ONLY TESTS**
 - **NEW INTERMEDIATE HUMIDITY/TEMPERATURE TEST LEVELS**
 - **POSSIBLE RETESTING WITH NEW GENERIC MODULE TYPES**
- **DETAILED FAILURE MECHANISM ANALYSIS AND DETERMINATION OF FUNCTIONAL DEPENDENCE**
- **CORRELATION OF LONG-DURATION TEST DATA WITH PAST AND FUTURE CLEMSON CELL TESTS**
- **REPORTING**
 - **FAILURE-MECHANISM STUDY RESULTS**
 - **RECOMMENDATIONS FOR IMPROVED QUAL TEST PROCEDURES**
 - **BLOCK VI**
 - **INTERNATIONAL STANDARDS (IEC)**

PROJECT ANALYSIS AND INTEGRATION AREA

R. W. Aster and G. Fox of the Project Analysis and Integration Area (PA&I) presented a simulation program that investigates the relationship between manpower requirements and equipment availability in the presence of scheduled and unscheduled maintenance. The program is called the Personnel Simulation Program (PSP).

PSP runs on a microcomputer, and was used to check the accuracy of the cost projections made by Kayex Corp. for Czochralski ingot growth. The methodology can be used for any type of equipment or for several types of equipment sharing common operators or maintenance personnel. PSP can be an important tool for optimizing capital-investment and labor-cost tradeoffs.

R. E. Daniel of PA&I presented a method for optimization of metallization patterns at a Cell and Module Formation Research Area technological session (see p. 363 and p. 378).

MACHINE/OPERATOR REQUIREMENT SIMULATIONS (Using the Personnel Simulation Program)

JET PROPULSION LABORATORY

R.W. Aster
G. Fox

The Problem

The Personnel Simulation Program (PSP) Was Developed to Investigate the Relationship Between Manpower Requirements and Equipment Uptime (i.e., Duty Rate) in the Presence of Scheduled and Random Downtime.

In the Absence of Long-Term Experience With Pilot Plants, MEPSDUs, and ESGUs, This Analysis Approach Can Assist in the Validation or Correction of Assumptions Made by Process and Equipment Researchers.

Essentially, PSP Can Be Used to Determine the Degree to Which an Industrial Process Has Been Successfully Automated

The Classical Operations Research Model The Case of Identical Work Stations

- **Steady-State, Birth-Death Model**
- **Failure and Restoral Rates (Events/Minute) are Independent of Event Histories**
- **Work Stations All Have Identical Failure and Restoral Rates, and Required Personnel**
- **Personnel Availability Can Be Stochastic**

PROJECT ANALYSIS AND INTEGRATION AREA

The General Iterative Model An Extension of the Classical Model

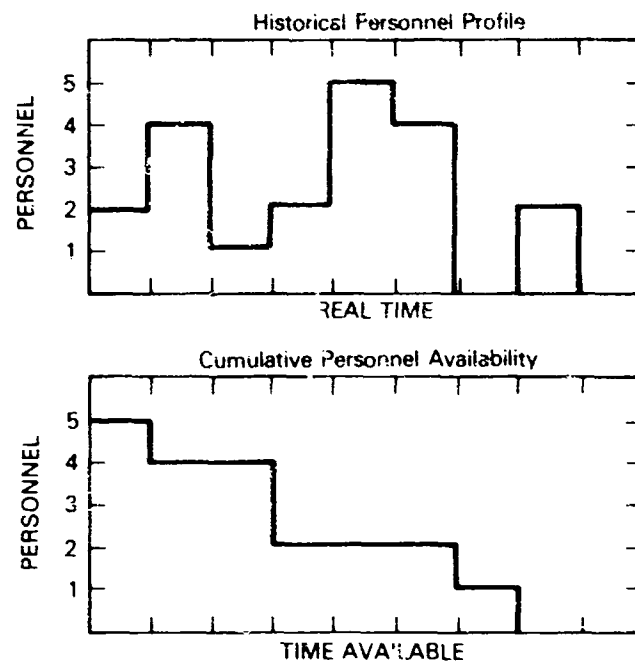
- **Steady-State, Birth-Death Model**
- **Arbitrary Failure and Restoral Distributions Without Loss of Memory**
- **Service Discipline is by Assigned Priorities. With Preemptive Rejection**
- **Personnel Availability Can Be Stochastic**
- **Work Stations Need Not Be Identical**
- **Multiple Personnel Requirements per Work Station Can Be Analyzed**

Input/Output Data

- **Input Maximum Number of Operations**
 - **Percentage of the Time Each Operator is Available**
- **Input Number of Work Stations**
 - **For Each Work Station Input**
 - **Average Time to Failure**
 - **Average Time to Restoral**
 - **Minimum Number of Operators Required to Service/Set up**
 - **Work Stations Are Input in Priority Order**
- **Output Data for Each Work Station**
 - **Percentage of Time in Operation**
 - **Percentage of Time Being Serviced**
 - **Percentage of Time Waiting for Service**
- **Output Data Final Operator Availability Table**

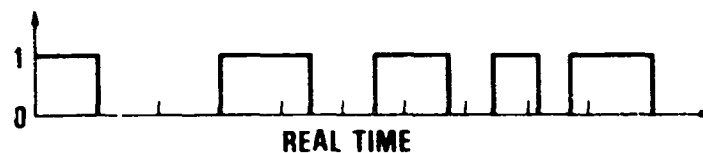
PROJECT ANALYSIS AND INTEGRATION AREA

Deriving Input Data



Construction of Failure and Restoral Distributions

- Sample Duty Profile of Work Station



- Average Time to Failure is the Average of the Lengths of Time Between a Failure and the Previous Restoral to Operation
- Average Time to Restoral is the Average of the Lengths of Time Between Restorals to Operation and Their Previous Failure Events

PROJECT ANALYSIS AND INTEGRATION AREA

Example Calculations

Based on Kayex Projections of 6-inch Cz Ingot Pullers

5 Ingots per Crucible

6-Inch Diameter

4 Operations:

- 1. Preparation (Load Si, Melt)**
- 2. Growth (1st Cycle)**
- 3. Recharge and Growth (4 Times)**
- 4. Clean Up and Set Up for Next Crucible**

Total Run Time 4680 min

Total Growth Time (Kayex Estimate) 2350 min

Total Operator Time (Estimated) 890 min

Furnaces/Operator/Shift (Kayex Estimate) 6

15% Idle Time in Addition to Run Time (Kayex Estimate)

Duration of Activities

	<u>Operator Minutes</u>	<u>Machine Minutes</u>	<u>Full Time</u>
Preparation	60	200	
Growth	60	680	470
Recharge/Growth (4 Times)	170	915	470
Clean and Set Up	90	140	

PROJECT ANALYSIS AND INTEGRATION AREA

Sensitivity Analysis I

Ingots Per Run	Perfect Schedule*			Stochastic Schedule**	
	Furnaces Per Oper.	Pull Ratio***	Inches Per Shift	Pull Ratio	Inches Per Shift
1	4.1	0.461	45	0.378	36.3
2	4.3	0.486	50	0.408	39.2
3	4.4	0.495	52	0.419	40.2
4	4.4	0.499	53	0.424	40.7
5	4.5	0.502	54	0.428	41.1

*Non-Integer Machines per Operator, 85% Operator Availability, Operators and Furnaces Never Idle

**4 Furnaces per Operator, Long-Term Average Idle Time for Equipment and Operators, but No Breakdowns

***Time Spent Pulling Usable Ingot Divided by Total Time

Efficiencies of Scale

Operators	Furnaces	Pull Ratio	Inches/Shift/Operator
1	3	0.473	34.1
1	4	0.428	41.1
1	5	0.376	45.1
2	9	0.420	45.4
4	18	0.433	46.8
10	45	0.473	51.1
Perfect Schedule	4.5	0.502	54

Sensitivity Analysis II

There Are 3 Types of Failure Modes:

1. Lose Ingot - Recover by Recharging and Restarting
Possible Reason: Ingot Turns Polycrystalline
Time to Recover: 347 Machine Minutes, 70 Man-Minutes
2. Lose Run - Recover by Completing Poly Ingot, Cleanup, Restart
Possible Reasons: Crucible, Ingot, Raw Si Problems
Time to Recover: 375 Machine Minutes, 80 Man-Minutes
3. Damage Equipment
Time to Recover: Not Available From Kayex at This Time
(Accounted for by 15% Down Time)

At What Frequency of Failures Do You Pull Fewer Ingots?
Based On: 4 Furnaces per Operator, 5 Ingots per Run, Variable
Frequency of Type 2 Failures in Last Ingot

<u>Case</u>	<u>Frequency</u>	<u>Pull Ratio</u>	<u>Inches/Shift</u>
A	0%	0.428	41.1
B	5%	0.425	40.8
C	7%	0.424	40.7
D	10%	0.422	40.5

Conclusion (Based on Incomplete Example Data): If the Growth of the 5th Ingot Fails 7% of the Time or More, Then You Are Better Off Growing Fewer Ingots

Future of This Methodology

Development Steps.

- Incorporate a Submodel to Perform Capital/Labor Tradeoff Optimization for a Type of Work Station, Given an Output Requirement
- Expand Capability to Multiple Work-Station Types and Personnel Types and (Possibly) Buffer Inventories to Make Work-Station Interdependency Tradeoff Studies
- Document and Make PSP Widely Available for Applications